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PANEL ON UNDERWATER ACOUSTICS

COMMITTEE ON UNDERSEA WARFARE

NAS - **NATIONAL RESEARCH COUNCIL**

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This volume is one of a series of survey reports prepared for the Office of Naval Research by technical advisory panels of the National Research Council Committee on Undersea Warfare.

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Foreword

The Panel on Underwater Acoustics was established in 1947 as the first of a series of ad hoc technical groups to assist the Committee on Undersea Warfare in its task of advising the Office of Naval Research on its scientific and technical program relating to Undersea Warfare. In this capacity, the Panel agreed to review the status of current knowledge within the assigned scientific field and, on the basis of its findings, to recommend a peacetime program of research which could serve as a guide both for the intelligent direction of programs in progress, and for the formulation of additional or supplementary programs. Their report, which was submitted in its complete form to the Navy in September 1948, has now been made available in an unclassified version for the general benefit of research workers in this field.

The Navy, which provided the support enabling this study, is logically most concerned with those applications of underwater sound which appear to hold maximum promise of contributing to the nation's ability to defend itself against possible future undersea attacks. At the same time, however, it was wisely recognized by those responsible for planning and guiding the Navy's research effort that these applications cannot be definitely specified without scientific understanding of the physical phenomena and processes involved in the generation, transmission and reception of underwater sound signals; that maximum strength can result only from the combination of such knowledge and a trained and experienced body of scientists and engineers throughout the military and civilian laboratories of the nation.

As a consequence, it was decided that every effort should be made to disseminate the reports of these technical advisory panels on the widest possible basis that could be made compatible with the requirements of military security. This has been done in the case of the present report, with only those sections and recommendations bearing directly on military plans being deleted from the original report of the Panel. It is believed that these deletions subtract little if anything from the usefulness of the report to those who are actively interested in the several aspects of underwater acoustics research.

Since the date of submission of the original Panel report to the Office of Naval Research in September 1948, much of the research described in this report has been extended and, in some cases, new programs have been initiated along the lines recommended by the Panel. While it is regretted that it has not been feasible to include an account of the results obtained during this intervening period, these do not appear in any way to contradict or to modify seriously the Panel's findings. Rather, they tend to lend further emphasis to the desirability of a comprehensive and concerted attack on the major problems associated with the character and behavior of sound waves in the ocean.

The Committee wishes to take this further opportunity to express their very great appreciation to the members and associates of the Panel for a difficult and comprehensive job well done. By their efforts a means has been provided to bring together the research efforts of civilian and military scientists into a unified national program having force and direction. The helpful cooperation of the Acoustical Society of America and the American Institute of Physics who have assisted in the editing and distribution of this report is gratefully acknowledged. Finally, the gratitude of those who are professionally interested in the growth and

development of the science of underwater acoustics is due to the Chief of Naval Research and his staff for their continuing and understanding support of this and other critical fields of basic research.

The Committee on Undersea Warfare.

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Preface and Summary

Lyman Spitzer, Jr.
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The Underwater Acoustics Panel was set up to survey the status of basic research in the many different fields which constitute the science of underwater acoustics. The military importance of basic research needs no elaborate justification here. The development of radar and the atomic bomb in World War II are two convincing examples of decisive military weapons which were almost entirely a direct engineering application of basic research results obtained during the previous years. It may therefore be taken as established that over a long period undersea warfare will be effective only in so far as it is based on an active program of fundamental research in the relevant scientific fields.

While this means that the general importance of basic research can be accepted without further discussion, it is not immediately obvious which particular research projects in the field of underwater sound are most likely to increase the effectiveness of undersea warfare. In fact, the choice between alternative research possibilities in this field is a very difficult one and must be given careful thought to ensure a wise direction of effort.

The problem is complicated by the fact that the usefulness of research results depends not only on their general significance but also on the immediacy with which they may be applied. In some cases, results which are not very significant from a purely scientific standpoint may be extremely useful over the short run, and may be more desirable than a thoroughgoing explanation of some scientific field, which may take some time to translate into increased sonar effectiveness. Evidently, the nature of the research program to be followed depends on the time scale envisaged. A program designed to provide the most useful information in 25 years might be of little help in the event that sub-surface warfare were to become a reality within a few years.

It is easy to find numerous examples of research programs with either short-range or long-range objectives. The shortest-range research is that which is designed to improve the operation of existing equipment. The underwater sound transmission studies carried out during World War II provided an excellent example of this type of project. Results obtained in these studies were translated into specific rules for different types of anti-submarine action under different thermal conditions, and into corresponding rules for submarine evasion tactics, within less than a year after the observational data were obtained. This is very much shorter than the time lag between the design of most types of naval equipment and the effective use of this equipment at sea. Possibilities of this type of research with existing equipment were largely exhausted during the war. Perhaps the outstanding research problem of this type which might still repay considerable effort is the survey of sound conditions in the Arctic. Results obtained in such a survey can quickly be applied in the formulation of rules for the most

effective operation and deployment of existing equipment if naval operations in the Arctic should become necessary.

Research projects of intermediate range may be defined as those which are designed to obtain information directly needed in the design of contemplated equipment. Studies of surface reverberation made to facilitate the design of echo-ranging torpedoes provide an example of this sort of basic research. A search for new types of noise sources would provide important information in the design of countermeasures for acoustic torpedoes and is thus a project of intermediate range. Similarly, studies of transducer materials and acoustic cavitation, which would increase the power output of echo-ranging transducers, would also be of intermediate range.

Lastly, there is long-range research into fields of general interest, without any consideration of specific military application. Over the long run, this is by far the most valuable of all three types of basic research, since it provides a broad scientific understanding of the natural phenomena which may be utilized for military purposes. Such an understanding is required, for example, to indicate in detail what types of new equipment will and will not be practical. Perhaps the best example of this type of research would be a project entitled for instance, *Increased Accuracy of Underwater Sound Measurements.* At the present time no military applications can be foreseen for more accurate intensity measurements, although more accurate bearings would, of course, be directly useful. The history of progress in other sciences suggests, however, that increased accuracy of acoustic measurements may make possible an increase in our basic understanding of the underlying phenomena and ultimately lead to a more effective use of underwater sound in subsurface warfare.

In preparing the various surveys which form the body of the present report the Panel has been forced to make some relative judgements as to the time scale visualized for research in this field. In general, the greatest emphasis has been given to the long-range problems, to those research projects which would contribute to our broad understanding of underwater acoustics. However, the possibilities of more immediate application have been kept in mind, and basic information required for specific applications has been given emphasis in a considerable number of cases throughout the report.

The different surveys which constitute this report have each been prepared by a member of the Panel, in some cases with the collaboration of other scientists. Each survey is designed to review briefly the status of our present knowledge and to make recommendations for future research. For e[illegible] survey at least one other scientist has b[illegible]ed as an *official reader;* the read[illegible] in the general table of contents to[illegible]ith the different authors. These readers h[illegible]ch read the surveys assigned to them, and made comments and suggestions for revisions of the manuscript. These comments all have been very helpful and have in some cases led to major changes. However, the responsibility for the final surveys and for the recommendations which they contain rests entirely on the individual authors and on the Panel as a whole.

Since the formulation of research recommendations was felt to be the Panel's chief task, no attempt has been made to write a general handbook or encyclopedia of underwater sound knowledge. Adequate summaries of existing information in many fields already exist. Hence, in most of the following surveys the status of our knowledge has been described only to the extent needed to explain and justify the recommendations for further research. In a few cases, notably in the discussion of fluctuations, where no adequate discussion of existing information was available, a rela-

tively long summary of this information has been included.

The emphasis on basic information, as opposed to specific information needed for particular application, has already been discussed. In addition, emphasis has also been placed deliberately on the major gaps in our knowledge, regardless of whether work to fill these gaps is now in progress. Thus no extensive discussion is given of the amount of work now underway on most of the recommended research projects. Since in many cases the survey of a field has been written by the investigator who is now primarily concerned with work on this field, many of the research recommendations made in this report are already being carried out in part. However, in view of the relatively small scale of most present efforts, additional work on any one of the recommended projects would be thoroughly worth while.

It should be pointed out that the report is primarily written for those actively concerned with sonar research. In order to broaden the approach somewhat, an attempt has been made in each survey to insert sufficient explanatory material to permit anyone with a general technical background to follow the discussion and to understand the recommendations.

CHAPTER 1

Generation and Reception

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1. INTRODUCTION

The Need for Fundamental Research

The field of underwater sound is more than an engineering activity of concern only to warfare. It is also a field with challenging problems for fundamental research and an area of technology having diverse and important industrial applications.

There is a large and increasing interest in the applications of ultrasonic energy to problems in chemistry, biology, physics, food technology, industrial processing, and testing of materials. Sound has been reported to accelerate chemical reactions, break down high polymers, kill bacteria, homogenize milk, age whiskey, and accelerate the tanning of leather.

Such uses are relatively new, yet the promise of rich rewards from further basic research in this field grows daily. However, few applications have been reduced to rigorous engineering practice. In attacking new problems, one is often forced to employ trial-and-error procedures and empiricism because of inadequacies of fundamental knowledge in this field. Clearly, this situation calls for more extensive research, the fruits of which may be expected to aid both the industrial and the military applications.

In keeping with this picture, there is a growing need for scientists with specialized training in underwater sound. This need could be met in part by university curricula and in part by advanced research in academic, industrial, and government laboratories. This shortage could be alleviated further by increased activity in related fields of scientific interest. Experience with ultrasonics in liquids, in the study of physical and chemical processes, gives some of the background needed in underwater sound research.

These needs for fundamental research and for specialized training apply to many phases of ultrasonics and underwater sound, and they are particularly relevant to the present discussion of generation and reception. Here we deal with the basic tools of the field; instruments for sending and receiving sound are needed for experimental research in all applications of sound in liquids.

The Scope of the Present Report

This paper is written with two objectives: (1) to summarize in general terms the present status of underwater sound generation and reception and (2) to indicate lines of fundamental research which hold promise of contributing significantly to this field.

We realize that no report short of many volumes could summarize the extensive work in this field, the many techniques, and equipments. We must simplify and condense the supporting evidence. Probably some of the general conclusions we draw will be questioned from one point of view or another. In

anticipation of such discussion we wish to point out clearly the frame of reference in which this report is conceived. Our attempt is to generalize, in so far as generalization seems reasonable, and to emphasize major problems and minimize or ignore minor ones. This is not to say that lesser gains are not worth while.

The subject of sound transmission and reception, as viewed in this report, involves three aspects: (1) energy processing, (2) transduction, and (3) interaction with the medium. This classification is a somewhat arbitrary formalism; but its statement may serve to emphasize the breadth of the problem and to clarify the discussion of the various parts of the subject.

Under energy processing we include for a transmitting system the provision of power, amplification, control of frequency and signal dynamics, and any transformations needed before the energy is changed from its original form into acoustic. In a receiving system, energy processing involves the manipulation of signal energy after its conversion from acoustic to some other form. This may include detection, amplification, and modification of frequency or dynamic characteristics, preparatory to presentation of information in visual, audible, or graphical form.

Transduction is the changing of the form of energy between acoustic and any other form. In many underwater sound applications, this process occurs in a reversible transducer such as those employing piezoelectric or magnetostrictive materials. In so far as this is true, one can discuss simultaneously the transmitting and receiving properties of transducers. In some cases, however, the transducer is a sender but not a receiver. This is frequently the case for mechanical noisemaking devices. Or a receiving element, such as a carbon microphone, may not be useful for transmitting acoustic energy. Our discussion will cover all transducing mechanisms used in this field and will envisage the possibility of developing new substances.

Interaction with the medium includes the radiation reaction on the transducer, the radiation characteristics of transmission or reception in an idealized medium, and any effects which may be associated with cavitation. As contrasted with these influences of the immediate surroundings, the longer-range effects of transmission, refraction, and scattering in the medium are treated in other papers in this series.

This three-part classification shows that the transducer is not the only element in transmission and reception systems. However, it is the pivotal component and hence the logical focus of our discussion.

2. TRANSDUCER TYPES AND FUNCTIONS

Functional Requirements

Underwater sound transducers (defined in the broader sense) are used to perform a wide diversity of functions. These uses, in turn, require greatly differing characteristics of the transmitting and receiving systems. These differences may lie in size and space limitations, in power or sensitivity, in directionality of radiation or reception, in ruggedness and serviceability, and so forth. A good transducer for one purpose may be unsuitable for another.

To aid this study, let us outline the main applications of underwater sound equipment and the typical performance characteristics required for each function. In the subsequent section we discuss present types of transducers and the degree to which they are applicable for the various functions. The following list is in no way a complete statement of equipment design specifications. Rather, it is a general indication of kinds of uses and demands, given here as a framework for our discussion of research needs.

Echo-ranging transmitters generally call for:

(a) high power output, up to many kilowatts in some applications;
(b) fair degree of directionality, usually in a search-light beam or a narrow flat beam;
(c) relatively narrow frequency band width, perhaps up to a half-octave for some purposes;
(d) frequencies from 5 to 100 kilocycles, though special applications may use frequencies much lower or as high as 50 megacycles and some research has been carried to the order of 1,000 megacycles;
(e) relatively high efficiency;
(f) long service life.

Echo-ranging receivers frequently use the transmitting transducers, with the above requirements. In other cases, special needs include:

(a) medium or high directionality, sometimes in a beam of special or critical shape;
(b) reasonably high sensitivity and efficiency;
(c) medium or narrow band width, except in special search receivers which need wide band;
(d) long service life.

Listening receivers usually need:

(a) a broad, flat frequency coverage, up to a band of 15 kilocycles for audio listening, and perhaps more for heterodyne systems in which various bands are to be selected by the operator;
(b) either a sharply directional or a non-directional (in a plane) characteristic;
(c) high sensitivity and low noise level;
(d) long service life.

General noise sources usually involve:

(a) highest possible output of acoustic power;
(b) broadest possible band of noise, sometimes more or less flat, and sometimes with shaped spectrum or dynamic characteristics;
(c) non-directional radiation;
(d) short service life if of the expendable type, but long life desirable for other types.

Instruments for standards and calibration have critical requirements for some properties. In contrast with most other applications, however, this category does not usually demand high efficiency. Most of these instruments fall into one of two categories:

Non-directional field standards, which require:

(a) rigorously non-directional (at least in a plane) output;
(b) wide, flat frequency response;
(c) stable performance over long periods and under a wide variety of temperatures and other field conditions;
(d) wide dynamic range;
(e) portability.

Laboratory instruments for calibration and research, which usually need:

(a) medium directionality (enough to "cover" the device under test) and smooth directional response characteristics;
(b) reasonably broad frequency response, with smooth and preferably flat characteristics;
(c) performance stability in all regards;
(d) reliable and accurately known dynamic characteristics (dynamic range, transient response, peak handling capacity).

Transducer requirements for special purpose industrial applications are not considered explicitly in this report. Indeed, the newness and diversity of this field make it difficult to generalize industrial needs at this time. One can visualize, however, that most of the performance characteristics included in the above list may prove applicable to other fields.

Acoustic inspection of solid objects, oceanographic studies, sub-surface mapping, and the influencing of chemical and biological processes run the gamut of transducer capabilities. It is safe to predict that fundamental advances in any aspect of transducer technology will be beneficial both to scientific research endeavors and to military and industrial applications.

Types and Characteristics of Transducers

For our present purposes we may list the types of underwater sound transducers as:

(1) piezoelectric (natural and synthetic crystals);
(2) magnetostrictive;
(3) electromagnetic: moving conductor and variable reluctance (except magnetostrictive listed separately):
(4) electrostatic (except piezoelectric listed separately);
(5) carbon;
(6) mechanical (hammer, rods, siren, Rayleigh disk, etc.);
(7) chemical (explosive);
(8) thermal.

Of these several types of transducer mechanisms, magnetostriction and piezoelectricity are today the most adaptable to a wide variety of uses. For this reason, a large fraction of all underwater sound transducers in use today employ one of these two principles. Although fairly versatile, electromagnetic and electrostatic transducers are less common. Large numbers of carbon, mechanical, and chemical transducers have been used for specialized tasks, so that these types also form a sizeable fraction of the total transducer "population." The only thermal transducers used to date have been thermophones as absolute calibration standards, and heated wires to produce boiling noise in ordinary liquids[1] or "second sound" in liquid helium II.[2]

Of these types, magnetostrictive, piezoelectric, electromagnetic, and electrostatic are the only ones which, in their present embodiment, can be made linear and reversible. These properties greatly simplify the production of controlled signals which can be tailored to a wide variety of needs. It is not apparent that chemical and mechanical transducers are inherently less controllable; indeed they might even be made linear and reversible. The importance of examining this question is discussed in Section III. Carbon microphones have been investigated thoroughly and were widely used at one time. Although nonreciprocal, they are approximately linear receivers over a reasonable range. They are less often used today because of high self-noise and instability. Thermal devices have not been exploited fully, but they do not seem to offer great promise of new uses.

Both magnetostriction and piezoelectric devices have been applied widely to all of the applications listed in Section I, and all standard echo-ranging systems today use one or the other of these. Electromagnetic transducers could, in principle, be used in all of these applications, but practical considerations tend to limit this type to low frequencies because of the sizeable masses involved and the difficulty of designing efficient magnetic circuits at high frequency. These are not fundamental difficulties, and at least one successful high frequency (above 20 kc), high power moving conductor transmitter has been built. A small number of electromagnetic transducers are used in calibration instruments, and some have been designed for echo-ranging transmitters and receivers.[3]

Condenser microphones have been used by several laboratories as receivers, for calibra-

[1] M. F. M. Osborne and F. H. Holland, J. Acous. Soc. Am. **19**, 13 (1947).

[2] Peshkov, J. Phys. U.S.S.R. **10**, No. 5, 389 (1946).

[3] For example: *Operating Notes for NDRC 1A and 2A Standard Pressure Gradient Hydrophones BTL* (June 16, 1945); *Operating Notes for NDRC 1K Type Projector BTL* (May 9, 1945); *Operating Notes for NDRC 4B Projector BTL* (May 25, 1945).

tion, field measurements, and control mechanisms, in or below the sonic range of frequencies. This type is readily adaptable to pressure measurements at very low frequencies or even to static pressures. Although some research has been done on high frequency electrostrictive devices, these have not been used in underwater sound practice.

Carbon microphones have been used as receiving elements in acoustic mines, and in early forms of listening equipments. This type of transducer is not readily adaptable to sound generation.

During the last war there was considerable development of mechanical (hammers) and chemical (explosives) transducers. Such devices are comparatively inexpensive and compact, and deliver considerable acoustic noise at low efficiency. The output spectrum is subject to only gross control, and such systems have not been widely used.

Because of their versatility, magnetostriction and piezoelectric devices have been studied extensively and are moderately well understood. They are inherently limited by the physical properties of the available active materials, and these limitations are known reasonably well.

3. LIMITATIONS AND CAPABILITIES

It is helpful to distinguish among three kinds of limitations under which transducers are constructed: the laws of physics, the properties of available materials, and the inadequacies of theoretical and engineering knowledge.

Limitations imposed by basic laws are independent of particular materials and mechanisms and will not be changed by research. Of course, there is danger in confusing a really basic limitation with a lack of ingenuity or knowledge, and the apparently basic limitations must be examined carefully. The invention of the synchrocyclotron to overcome a limitation of the cyclotron illustrates the fruitful results of such scrutiny of "basic" laws. The other two kinds of limitations may be expected to be loosened, perhaps indefinitely, by research for new materials and by extensions of theory and technique. To describe the state of present practice and to uncover fields of needed research, we consider separately these three categories of limitations.

Basic Limitations

We need not list all of the physical laws which govern transducers; however, the following considerations are particularly relevant:

Directivity. The directivity pattern of a radiating surface is a definite function of the amplitude distribution and of the transducer dimensions measured in wave-lengths, irrespective of the transducing mechanism. In order to produce a prescribed pattern efficiently the transducer usually must be several wave-lengths wide in one or more dimensions. It may be possible, in principle, to obtain the pattern from a smaller radiator, but this would often require a complicated amplitude and phase distribution. The large velocity gradients across such a source lead to an unduly large radiation reactance. With a low power factor load the transducer's internal losses consume disproportionately high power, and the overall efficiency is very low. The optimum size is one employing a more nearly uniform velocity distribution with consequent high power factor. In several applications the optimum size is considerably larger than is convenient, and some important requirements are difficult or impossible to satisfy in practical devices for this reason. Since we are not likely to decrease the velocity of sound in the ocean, there is no reason to suppose that research could improve this situation for underwater sound.

Pulse Length. A finite segment of a sine wave contains a distribution of nearby fre-

quencies. As the length $\Delta\tau$ of the pulse is diminished, the width $\Delta\nu$ of the frequency spread increases so as to keep the product $(\Delta\tau \cdot \Delta\nu)$ constant. In most underwater sound work to date this has not been detrimental; the ping lengths have been so long that the frequency distribution has been negligible.

Limitations of Materials

Any transducer is subject to limitations imposed by the materials it contains. In practice the limitations imposed by electronic circuits are usually secondary compared with those of the transducing mechanism and the radiation medium.

In magnetostriction and piezoelectric devices the sharpness of resonance cannot be lowered below a minimum imposed by the transducing material itself (and the water), except by sacrificing efficiency.* Furthermore, the maximum power which can be radiated at any frequency, and the maximum sensitivity of a receiver, cannot exceed limits set by the materials available for transduction. Any high efficiency magnetostriction or piezoelectric transducer which can now be built, when operated into water out of an unequalized amplifier whose internal impedance allows the most efficient power transfer, has 3-db points at frequencies not more than one octave apart.

At present the ultimate limit on power output imposed by the transducing materials is very much higher for piezoelectric crystals than it is for magnetostriction metals. The magnetostriction device is limited by magnetic saturation, a property intrinsic to the present materials.

For several underwater sound applications it is necessary or advantageous to relieve these restrictions, but this can be done only by the discovery of new transducing materials.

The ocean itself imposes another important limitation through the phenomenon of cavitation. For pings at usual underwater sound frequencies, water cannot support intensities greater than, roughly, one watt/cm^2 at zero water depth. The exact value of this limit is not accurately known, nor is its dependence on temperature, frequency, depth, and other variables. Other liquids impose similar limits. A few liquids, such as castor oil, have been found capable of withstanding higher intensities without cavitation, but not by a factor large enough to relieve this limitation.

Cavitation is already a serious limitation on many underwater sound operations. The likelihood of demands for greatly increased power in future equipment makes this problem one of the most important in the field.

Inadequacies of Knowledge

There are many gaps in our knowledge of transducers, but the consequences do not often reduce achievable performance by as much as an order of magnitude below theoretical limits. The numerical values of most of the physical constants needed for transducer design are known within a few percent. The first-order theories of piezoelectric, magnetostriction, electrostatic, and electromagnetic devices are well developed, and transducer performance can usually be calculated reasonably well.[4] In most cases we can build transducers which perform within a few db of theory, at least if some trial and error is allowed.

We can achieve nearly any directivity pattern that is required, and we can usually do this without too many false starts by judicious use of theory and empiricism. In some cases a design may be required which is impracticable because of size or cost, usually because basic radiation theory requires a large array. It is then the laws of physics, rather than our own inadequacy, which force a compromise.

If very narrow beams (e.g., 1°) should be

* Throughout this paper "efficiency" is used in its customary sense: the ratio of the usable output power to the input power.

[4] W. P. Mason, *Electromechanical Transducers and Wave Filters* (D. Van Nostrand and Company, Inc., New York, 1942).

sought, considerable difficulty might be encountered. Such directivity would require greater control over the uniformity of construction than is now common. This is probably a problem to be treated by ordinary engineering methods. Split beams present an additional problem because of the reversed indication given by minor lobes. There is need for improved lobe-suppression schemes for this service. In present construction the direction of the acoustic axis and the position of the acoustic center tend to wander somewhat as frequency is varied; this is not serious now but might be in the future. Greater uniformity of construction is likely to help, but more thorough understanding of extraneous resonances and of unbaffled radiators is needed.

One method of extending the useful frequency range of a system is to group together several transducers having different resonant frequencies. However, at the cross-over frequencies where two or more units are radiating at comparable output level, the directivity pattern is usually very poor. To solve this problem we must know more about the phase shift characteristics of transducers and the properties of multiple radiators.

No adequate theoretical treatment (nor adequate empiricism, for that matter) is available for radiators which have dimensions comparable with one wave-length and which are set in baffles other than an infinite rigid plane.[5] This now causes difficulty, particularly in the design of large arrays for low frequency listening.

Present transducers usually have efficiencies of 20 percent or more—sometimes of better than 60 percent. The presently achievable efficiency is not limited by any one source of dissipation, but by an accumulation of several. Research on such things as new cements, lower hysteresis metals, and less dissipative isolation material is needed to obtain even a 3-db improvement in the average transducer.

Usually only a few db of increase in output power for the same input could be expected, and this increase alone is not of great importance. However, if cavitation is suppressed then the maximum output power presently obtainable is limited by failure of crystal transducers. At high power the heat generated by a 10 percent loss may be the most important cause of failure. For this reason imperfect efficiency is, in some applications, a serious problem. In this connection we should note that very few crystal transducers could now be driven to the limit imposed by internal crystal failure. Since this ultimate limit is roughly 25 db above intensities now used in standard equipment (i.e., at least 100 watts per cm^2), it is evident that the causes of transducer failure at lower intensities should be studied. So far very little has been done in this field.

Achievable band width is severely limited by the physical constants of transducing materials. This band width may be spuriously broadened by mismatching the amplifier or by introducing electrical or mechanical resistance. These produce broadening by reducing the output at all frequencies, an effect which might better be produced by electric filters in the amplifier. In some cases the radiation impedance may be complex and frequency dependent in a manner which serves to increase the band width. This is not of general use, nor is it accurately calculable because of shortcomings in our theory of unbaffled radiators of size comparable with one wavelength. Present-day transducers come quite close to theoretical band widths, tending to be a little narrower and to have small irregularities in frequency response. The irregularities are small enough to be of little consequence in most applications, with the exception of transducer calibration in which very smooth response is a great convenience.

[5] For example: G. D. Camp, *Some Notes on Acoustic Boundary-Value Problems, Etc.* (UCDWR Internal Report, January 12, 1944); H. S. Stenzel, *Guide for the Calculation of Sound Processes* (in German) (Verlag Julius Springer, Berlin, 1939).

Transducer designers can predict resonance frequencies within 5 or 10 percent with few exceptions. If closer control is required, a second model can almost always embody corrections which will make the error negligible for all practical purposes.

Temperature and time stability of transducers is adequate for most applications today, except for the critical needs of calibration and standards. (This statement excludes transducers containing X-cut Rochelle salt which has marked temperature dependence.[6]) It is likely that a great many effects contribute to the present observed changes, and several fields of research are indicated if greater stability is to be achieved.

It should be emphasized that our ability to approach theoretical limits of performance is based on considerable empiricism, and several false starts may be necessary. If construction techniques and construction materials were improved, if our knowledge of radiation theory were extended, if more accurate correction terms were known, then we could build cheaper, more reliable, transducers in shorter time. However, the final model would not be greatly superior to present devices except, perhaps, in ultimate power output. Engineering research in these directions is certain to benefit the economy of transducers, but it may not help greatly in solving the more serious problems facing undersea warfare.

So far, in this section, we have considered the reciprocal electromechanical transducers. One can say much less about chemical and mechanical devices. Little is known about their general capabilities as to achievable directivity patterns, efficiencies, band widths, and power outputs. If the performance obtainable with reciprocal electromechanical transducers were entirely adequate for our needs, this ignorance of mechanical and chemical devices might not be serious. Actually, there is an important need for better broad-band, high level sound sources. Research should be aimed at improving our knowledge of this subject.

4. DISCUSSION OF RESEARCH PROBLEMS

Many research needs are implied in the foregoing review of transducer limitations and capabilities. Four fields stand out as offering possibilities of major advances: (a) materials for transducers, (b) cavitation, (c) radiation theory, and (d) mechanical and chemical mechanisms.

Besides these, there are many important and interesting problems for which solutions are needed. Some of these are fairly certain to yield to attack, but the likely gains are smaller than those envisaged in the other four fields.

Materials for Transducers

It was indicated above that in many ways transducer design is now limited by the properties of available transducing materials. The achievable receiver sensitivity, transmitter band width, and maximum power output illustrate this. If piezoelectric or magnetostrictive transducers are to undergo major improvement in these respects, new crystals and new metals must be found.

These new crystals and metals should have greater electromechanical coupling,* and lower characteristic impedance (more nearly

[6] For example: See reference 4 and D. K. Froman, *Fundamental Studies on X-Cut Rochelle Salt* (UCDWR Report, July 15, 1945).

* In magnetostriction or piezoelectricity the coupling between the electric or magnetic field and the elastic stress field is intrinsic to the material. Under static deformation the ratio of the electric or magnetic field energy to the elastic energy is equal to $(1 - k^2)/k^2$ where k is the electromechanical coupling coefficient. The values of k for Y-cut Rochelle salt and Z-cut ADP are about the same ($k \sim 0.3$). The value for X-cut quartz is lower ($k \sim 0.1$). In X-cut Rochelle salt k is strongly dependent on temperature and electric field; under some conditions the value is quite large. The values of k for magnetostrictive metals cover a wide range, but rarely are as large as 0.3. Very considerable advantages would be obtained if a new material with $k \sim 0.5$ or more could be found.

equal to that of water),[7] and should have higher power capabilities. In order to be of greatest use they should have temperature stability, linearity over wide dynamic range, and low internal dissipation. While not of primary importance, it would facilitate production considerably if such new materials did not require very close control of chemical impurities or heat treatment.

The search for new piezoelectric crystals and new magnetostrictive materials has already yielded several useful crystals and new materials such as ADP and Permendur. Fundamental efforts along these lines should be continued, with active support. These researches on magnetostrictive metals and on piezoelectric crystals should be fully integrated with general advances in solid state physics. The few people engaged in research on electromechanically coupled materials are aware of the importance of this integration, but interest in this field is not widespread. Those concerned with other aspects of the solid state should be encouraged to consider these materials as aids in their own work and as subjects for study.

Transducers employing other (electromagnetic, electrostatic, resistance) mechanisms have been carried to various stages of development. Here, too, are needs for more favorable materials, but the desired properties are less clearly defined than in the two cases discussed above. Also one can visualize new materials which possess transducing properties not yet utilized in this field. For example, the conductivity of an electrolyte has been reported to vary with pressure;[8] strains in some solids can be measured optically; in mechano-electronic microphones, mechanical motion of a vacuum tube element modulates an electric signal.[9] Such approaches should be given consideration, and new effects sought.

Cavitation

Cavitation is understood to be the rupture of a liquid subjected to large negative pressures. It is readily produced both hydrodynamically and acoustically, and often leads to extensive mechanical damage as well as non-linear transmission of sound.

A more detailed examination indicates that several observable phenomena are associated under the generic name "cavitation,"[10] and it is not clear which one can be regarded as the primary phenomenon. To cite a few of these: cavitation is generally accompanied by the formation of visible bubbles of size depending on the other physical variables; there is often an audible frying noise thought to be produced by bubble collapse; severe erosion of solids is thought to be caused by bubble collapse; visible light may be given off; oxidation reactions appear to be accelerated; acoustic transmission becomes non-linear. Not all of these need be observed in any one experiment, and those which are observed are not always present to the same extent. One may produce clouds of bubbles from a crystal face for several hours with no audible sound and no erosion. Alternatively, one may observe non-linear transmission effects before other phenomena are detectable. The divergence of views which exists in this field may be due, in part, to differences in criteria which have been used for the presence of cavitation.

Thus it is evident that the term "cavitation" needs more precise definition. It may turn out that hydrodynamic and acoustic cavitation are such widely different aspects of the funda-

[7] Briggs, Johnson, and Mason, "Properties of liquids at high sound pressures," J. Acous. Soc. Am. **19**, 4, 664 (1947).

[8] G. D. Rock, "The effect of ultrasonic waves on the conductivity of salt solutions," Phys. Rev. **70**, 329 (1946).

[9] H. F. Olsen, "Mechano-electric transducer," Paper No. 48—Thirty-Second Meeting A.S.A., abstract in J. Acous. Soc. Am. **19**, 1, 291 (1947).

[10] For good bibliography of "effects" in 1939 see W. T. Richards, "Supersonic phenomena," Rev. Mod. Phys. **11**, 1 (1939).

mental process that they should be distinguished by separate names.

Recent work has shown clearly that the most elementary model of the cavitation process is inadequate; the liquid does not rupture every time the negative pressure exceeds some minimum. A more detailed model of a liquid, perhaps employing quantum mechanics, is needed. A study of these phenomena should be of considerable interest to those concerned with the theory of the liquid state.

Besides the theoretical approach, we need extensive experimental measurement of the dependence of acoustic cavitation in various liquids on the physical parameters of the system. There is reason to believe that the following variables may influence acoustic cavitation:

(a) chemical nature of the liquid,
(b) acoustic pressure,
(c) acoustic intensity,
(d) static pressure,
(e) pulse length,
(f) repetition rate,
(g) temperature,
(h) micro- and macroscopic nature of the solid radiating surfaces (if cavitation occurs there),
(i) past history of the liquid (perhaps for over an hour),
(j) dissolved gases,
(k) suspended solids,
(l) geometry of the wave fronts,
(m) frequency.

Considerable progress has been made in the understanding of some of these dependencies, but none of them has been studied exhaustively. In no sense have we an adequate understanding of these many variables and their complicated interrelations. Such understanding might lead to means of raising the limit on output intensity and of avoiding erosion damage. The above list is striking evidence of the breadth of fundamental research this field offers.

Radiation Theory

Adequate solutions for the directivity pattern and radiation impedance are available, or readily calculable, for radiators of almost any description, at the two limits of very high and very low frequency.[11] Relatively few problems have been solved, even approximately, in the intermediate case. Most of those which have been solved deal with radiators set in rigid baffles which are either plane, spherical, or cylindrical. Recently an accurate solution for the unbaffled thin-walled organ pipe has been obtained by a new variational method.[12] This notable success in a classic problem gives hope that many other difficult radiation problems may soon be solved.

Typical examples of directivity problems arise in the field of low frequency directional listening. For this application an array of hydrophones may be distributed over a large part of the hull of a ship in order to obtain sufficient directionality.[13] The hull is not rigid or plane or large compared with the array. The directivity pattern cannot be calculated accurately today, and satisfactory results are difficult to obtain.

In other cases the radiation impedance is of major importance because of its effect on transducer resonance frequency and band width. The inability to compute this impedance for many commonplace arrays is a serious handicap.

These examples are not the only ones of importance. There is need for a general method of attacking the theory of radiators of size comparable with one wave-length and set in baffles of arbitrary size, shape, and impedance.

[11] For example: Rayleigh, "Theory of sound." Also, M. Lax and H. Feshbach, "On the radiation problem at high frequencies," J. Acous. Soc. Am. 19, 4, 682 (1947).

[12] H. Levine and J. Schwinger, Phys. Rev. 73, 383 (1947).

[13] "The German use of sonic listening," J. Acous. Soc. Am. 19, 4, 678 (1947).

Even less general solutions for particular configurations such as these would be welcome:

(a) A uniformly, radially vibrating circular cylinder of arbitrary diameter and length, each comparable with the wave-length, without end baffles, and with arbitrary impedance of the top and bottom plane surfaces.

(b) A long square prism whose cross-section dimensions are comparable with the wave-length; one pair of opposite faces driven uniformly in phase (i.e., both move outward at the same time) at the same amplitude; the other pair of faces passive but arbitrary impedance.

(c) The point radiation impedance seen at any point in a flat circular or rectangular piston of dimensions comparable with the wave-length, vibrating uniformly, and set in an arbitrary baffle (or the special case of a rigid plane baffle).

Mechanical and Chemical Mechanisms

Some of the broad band, high level output requirements for counter measures are virtually unobtainable by present kinds of electronically driven reversible transducers. Short of drastic improvement in active materials, only the development of wholly new mechanisms or extensive exploitation of other old mechanisms holds promise of satisfying these needs. Mechanical and explosive devices have already been used for a variety of functions, and one can visualize considerable extension of these methods.

It is not easy to systematize our knowledge of this field, or even to generalize the characteristics of the mechanical and explosive devices which have already been used. This is because the range of possibilities is very great and because there are major differences in the performance characteristics of the various devices involved. The chief point we wish to urge in this paper is the need for just such systematization and generalization of the subject. Possibly, after this has been done (on a broad basis as contrasted with development of a specific device), we will find that the field does not offer much beyond the results which have already been realized in practice. However, we see little reason for drawing this conclusion at the present time.

In at least one direction, the exploitation of a classical principle has been most successful: the development of an efficient high power air siren.[14] Here modern methods and materials have produced a device capable of much greater output than any present electroacoustic device for sound in air, and at an efficiency above 50 percent.

One could cite many more examples, but this would detract from the generalization we seek to establish. We are not proposing specific "inventions." Rather, we are suggesting that an exploratory program be carried out along very general lines. This program should involve extensive theoretical analysis and critical experimentation, and should aim to assess the inherent potentialities and limitations of mechanical and chemical mechanisms for acoustic transducers.

Such a program might seem a throwback to the nineteenth century. However, we now possess metals, bearings, gears, fuels, and production tools greatly superior to those available in the days before electronics. With these, and with the more advanced and widespread theoretical background, we might be able to evolve efficient, rugged, and versatile devices.

Other Problems

There are many other problems, largely in the nature of applied physics, which have important bearing on the continued advancement of underwater sound. These can be more specifically described and their contributions

[14] R. C. Jones, "A 50 horsepower siren," J. Acous. Soc. Am. 18, 371 (1946).

more readily predicted than can the broad problems discussed above.

Some of these problems involve, primarily, electronics; three in particular may be noted: (a) comprehensive study of the performance of electronic amplifiers working into reactive loads (particularly at high level in steady state and in short duty cycle), aiming at convenient design methods and charts;[15] (b) review of the importance of circuit noise in underwater sound applications, giving particular scrutiny to the causes of very low frequency noise; (c) instrumentation in general and, more particularly, the development of wide-range instruments suitable for study of noises having large peak-to-r.m.s. ratio; (d) study of the economy of energy storage in batteries, springs, compressed air, and other such devices, including evaluation of energy/weight, energy/volume, internal impedance, and efficiency of recovery.

Among the problems related to transducing mechanisms are: (a) development of electrostatic and electromagnetic transducers, taking advantage of their flexibility of design; (b) exploration of numerous possibilities of obtaining high power and broad band width from new materials and mechanisms; (c) systematization of transducer design information, and correlation of the information and terminology of the piezoelectric, magnetostrictive, and electromagnetic fields; (d) development of passive materials for transducers; (e) measurement of mechanical properties of many passive materials at appropriate frequencies; (f) full development of transducer theory to the second-order approximation, including the reduction to design charts.

In connection with the radiation medium, at least two problems are notable: (a) investigation of the influence of turbulence on sound propagation and on acoustic cavitation; (b) derivation of a simple algebraic (as opposed to integral) method of computing the reverberation index of the more common radiators.

5. CONCLUSION: SUMMARY OF RECOMMENDATIONS

Let us conclude this survey with a brief summary of the research problems which appear to be important for underwater sound generation and reception. We do not imply, by omission, that other lines of research are unlikely to yield improvements in this field. But we believe that the problems stressed here are the most likely to remove major deficiencies in present knowledge, or to yield major advances if the research is "successful."

Transducing materials should continue to be studied extensively. More favorable piezoelectric or magnetostrictive substances could yield outstanding gains in underwater sound generation. Although extensive searches for new materials have already been made, and although the needed degree of improvement is not yet in sight, we know of no proof that the desired characteristics are physically unattainable. In this connection, attempts to generalize the knowledge on a fundamental chemical and physical basis should be encouraged, for only by this path are we likely to gain the ability to design new materials from first principles.

Cavitation is a subject of fundamental physical interest as well as one which has important bearing on sound generation. A large number of unanswered questions on this subject are enumerated in Section III.

Radiation theory has been developed to a high degree in recent years. However, there are many particular directions in which refinement and extension of theory would aid underwater sound investigations. New analytical methods of increased generality or tractability would benefit this field in many ways. Such studies are also important to many other fields

[15] The methods now available are inadequate and tedious. See, for example, Radio Engineer's Handbook, Terman; McGraw-Hill, 1943, page 382.

of physical research so that we may expect continued progress along these lines. However, progress in other fields should be interpreted specifically for acoustics problems.

Chemical and mechanical processes for sound generation should be investigated from many points of view. Though the basic phenomena may be well understood, much can be done to generalize and synthesize knowledge of these phenomena for transducer applications. Some problems for study might include impact excitation of mechanical systems, cavity resonators and other linear systems, the characteristics and control possibilities of chemical energy in sound generation, and a general study of ultimate power capabilities in terms of size limitation.

A number of other problems, largely in applied physics, are of demonstrable importance to underwater sound generation and reception. These problems differ somewhat from the four discussed above, in that new general principles are less likely to emerge, but these are problems which call for a high degree of research skill and imagination.

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CHAPTER 2

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Standards and Calibration Methods for Measurements

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1. INTRODUCTION

The Need for Improved Standardization

A survey of underwater sound calibration facilities throughout the United States shows a large number of stations and laboratories which include as a major or minor part of their functions the calibration and evaluation of the underwater acoustical devices which they develop or use. This measurement work is essential to every research or development program and can best be carried on at the location where this work is in progress. Approximately twenty laboratories in the Navy, universities, and industry have adequate, and often elaborate, calibration and measurement facilities. (See appendix.) This situation requires that close coordination of these laboratory facilities exist in order that all underwater sound programs can benefit by the use of first-class calibration equipment and measurement techniques.

Thus the continued development of acoustic standards and calibration methods and techniques for underwater sound measurements will always be vitally necessary. This work should be carried on at all laboratories having underwater sound measuring facilities, and in particular at the Underwater Sound Reference Laboratory, which was established and is maintained by the Navy to carry on both experimental and theoretical investigations leading to standardized methods and techniques for calibration and testing in all types of underwater sound measurements. The work of standardization and calibration includes not only methods directly applicable to the absolute and relative calibration of all primary acoustic standards used in laboratory measurements, but also to methods for standardization of all secondary standard hydrophones and projectors used by research groups, development laboratories, manufacturing plants, Naval bases, and ship and shore sound installations. The over-all work of standardization constantly aims to improve the accuracy of the measurement techniques in use by all these agencies. At the same time, simple procedures must be maintained, making it possible to expedite the intercomparison of the sound measuring equipment of the various groups at periodic intervals and especially with the standards of the Underwater Sound Reference Laboratory. It is important that the staffs of all laboratories include technical people who have sufficient time to carry on accurate measurement programs for their own work and who can also maintain the essential liaison activities between laboratories.

From time to time the progress in the art of underwater sound measurements should be reported to the American Standards Association for adoption into its terminology and definitions for underwater sound. Each new general development for the comprehensive field of

underwater sound equipment requires the adoption of certain new definitions and terms for the adequate description of the calibration and expected performance of the gear. Experience has shown that final general acceptance and use of such definitions and terms is best assured by having as wide a participation as possible of all interested groups in their preparation. This mechanism is afforded by the recognized procedures of the American Standards Association.

The development of new sound projectors and hydrophones to serve as standard instruments for underwater sound measurements calls for a continuing development program. It should be emphasized that even today, after the very great effort made during and since the war to develop standard instruments, there are none at present available that are really adequate for precision measurements to 0.1 db or less. The principal need for this accuracy is in basic scientific research in this field. For this development the cooperation of every organization doing underwater sound work will be required, and specific developments should be arranged for by means of contracts with industrial and university laboratories for the production of improved instruments. Specific recommendations for this program are given below.

It should be the responsibility of the Underwater Sound Reference Laboratory to calibrate representative samples of all sonar devices, not only hydrophonic standards and measurement instruments, but also type models of all acoustical equipment. Data from these tests would form the source material for a frequently revised *Handbook of Underwater Acoustical Devices*. This *Handbook* would assist in the over-all program by disseminating technical information on underwater sound measurement procedures and checking on the performance of measurement equipment and standards for various tests.

The Role of Standardization in the Development of Navy Gear

The testing of underwater sound devices assumes two forms, depending on the type of information desired. In one type of test, the objective is to obtain data which characterizes the device independent of its environment to such an extent that its behavior in any particular environment can in principle be predicted. Such an evaluation constitutes a *calibration test*. It should not only evaluate the acoustical features of the device, but also the related electronic and mechanical components. This is the type of test which the Underwater Sound Reference Laboratory should carry out systematically on all sonar equipment. The second type of test is planned to take special heed of the particular application for which the device is designed, and it is usually essential to obtain directly information bearing on its efficiency in carrying out the assigned task under the actual conditions which prevail at sea. Such an evaluation of a device is known as an *operational test*. These tests are carried out by various groups and are obviously not the proper function of calibration laboratories.

The essential difference in the two methods of testing is this: A calibration test is made under carefully controlled conditions with the object of eliminating all extraneous factors entering into the measurement which represent characteristics of the environment rather than those of the device itself. In an operational test, however, the environmental factors are of dominant importance, thus making the performance depend not only on the intrinsic characteristics of the gear, but upon the peculiar characteristics of the surroundings at the time of the test as well. However, a satisfactory and complete operational test requires the knowledge of the inherent performance of the device itself which can be obtained only from a calibration test of the equipment. In principle, these data, together with those of sea

conditions, should permit a prediction to be made of performance in any environment. While this ideal is still far from realization in most cases, yet it should never be lost sight of in planning a program for fundamental research in underwater sound.

It should be emphasized that the calibration of an isolated projector or hydrophone will not always yield data which are directly applicable to the later use of this device as a component of a complete sonar equipment. It is, therefore, highly desirable that the entire acoustical device be studied and calibrated as a complete unit.

The data obtained by the calibration laboratories not only are necessary to supplement operational tests of sonar gear, but will be needed for the general *evaluation activities of the Navy*, based on calibrations, operational sea tests, sonar analysis, operational analysis, psychoanalysis ratings, experience with training devices, and reports from field engineers and Navy personnel. For the calibration data to serve their maximum effectiveness, they should be made available as widely as possible to the personnel engaged in each of the above activities.

The calibration reports of the Underwater Sound Reference Laboratory should be detailed and give the pertinent acoustical data on all standard hydrophonic instruments, on all sonar systems and other underwater acoustical devices, as well as every improvement in the techniques of underwater sound measurement and calibration. In all cases, consistent with security, these reports should be published in whole or in part in the scientific and engineering journals as contributions to the art. In this way, constructive criticisms of the work in underwater sound can be obtained from workers in other branches of acoustics.

It is recommended that once each year a Conference on Underwater Sound Measurements be held to discuss and demonstrate recent advances in acoustical measurement techniques, standard instruments, and methods of calibration of sonar gear. Representatives of each agency (see appendix) actively engaged in work in underwater sound should be invited to attend this conference, and those invited should especially include the laboratory workers actually engaged in making underwater sound measurements. The techniques involved are so specialized that only by active participation in the actual measurements themselves can the methods be effectively learned.

2. DEVELOPMENT PROGRAMS TO EXTEND CALIBRATION FACILITIES

The research problems listed below have been selected for special emphasis in the belief that future underwater sound developments will require increased accuracy in all measurements and greater development of methods and techniques for high frequency and high pressure calibrations.

Improvement of High Frequency Facilities

(a) Development of improved standards should make it possible to calibrate up to at least 10 megacycles (the present limit is 2.2 megacycles), the transducer capable of being used with very short pulsing circuits, both for calibration in tanks and for model studies of echo formation, transmission, etc.

(b) For the megacycle region, additional methods of calibration should be developed to supplement and check the reciprocity method which at present is the only one available for this region. Promising methods are those depending on radiation pressure, such as modifications of the Rayleigh disk, and optical methods which depend on the diffraction of light by the sound waves in the liquid.

(c) High frequency standards should be developed both for free field and tank calibrations, the latter especially at high hydrostatic pressures. This will require important ad-

vances in mounting and rigging techniques, and development of acoustic absorbing coating, good for 20 db absorption, if possible, and effective under high pressure and wide temperature variations.

(d) A most useful adaptation of the high frequency systems will be for model studies of echoes and the transient characteristics of diffraction patterns. It should be emphasized that the models should be elaborate reproductions to include all acoustic elements properly scaled. This will require extensive theoretical work on scaling factors and expert construction and mounting of the models. Only by the use of models can a large amount of the acoustic data needed be obtained with probable peacetime facilities.

Calibration under High Hydrostatic Pressures

(a) The range of calibration for all types of submarine sonar should be extended to 1,000 p.s.i. to duplicate conditions in the most modern and future submarines, and special calibration facilities should be provided for calibration of experimental hydrophones to 20,000 p.s.i. to duplicate conditions to be met in deep sea operation.

(b) Development of a method for measurement under pressure at frequencies between 100-10,000 cycles.

(c) Improved standards for these hydrostatic pressures should be developed, either from hard crystals, such as quartz, or electrostatic instruments made with a solid layer construction.

(d) The *self-reciprocity* method of calibration should be exploited for tank work because this method employs only one transducer and effects of hydrostatic pressure are immediately determined.

Pulse Techniques for Calibrations

(a) Pulse techniques should be developed for all types of tank testing, including high pressure tanks, tanks used for testing sonar gear in manufacturing plants, and also for special tanks used in research problems. As recommended above, absorptive coatings should be developed for use in tanks to take full advantage of pulsing methods. These coatings should be capable of 20 db reduction in reflections at all frequencies down to 1 kilocycle. They will also be essential for screens to reduce surface and bottom reflections as these factors strongly limit the accuracy of present calibrations.

(b) Eliminate cross talk between pulsing circuits.

(c) Methods should be devised to obtain high power for pulse calibrations without heating or cavitation.

(d) Pulse techniques should be especially developed for the calibration of sonar projectors. The transient response of an instrument is not given by steady-state measurements in at least two important particulars: first, the complete diffraction pattern often is not built up; and second, harmful breakups in response to transients do not usually show in steady-state calibrations.

Methods of Transient Analysis

Present methods are cumbersome in the recording and playback processes. In addition, development is required to obtain high level transducers for explosion and shock pick-ups.

Analysis of the Reciprocity Principle in Calibration

(a) Determine the practicality of the reciprocity method for reliable application at very high frequencies (megacycle range). The reciprocity principle of calibration is certainly sufficiently reliable for all practical work at the present time in the usual frequency ranges; nevertheless, the most effective employment of the reciprocity principle in calibration will require extensive research, both theoretical and experimental, into the limits of accuracy of this method, especially at the higher frequencies. Although at the present time such factors

as stray reflections produce errors in measurements greater than those inherent in the use of the reciprocity method, it will nevertheless be necessary to study every possible improvement and limitation of this method to meet the demands for increased precision in acoustical measurements. Among the factors which need careful study may be mentioned:

(1) Dielectric relaxation phenomena (especially at high frequencies) may set a limit on the applicability of the method, since the relaxation process may in effect make both the instantaneous and past history of the transducer affect the measurements;

(2) Electromagnetic radiation from transducers (again at high frequencies) that are not properly shielded may set a limit on the accuracy attainable by reciprocity.

The effect of radiation in general is that it makes the measuring of ordinary voltage and current readings difficult to define accurately. These effects may be expected to be small except at the highest frequencies, but their exact specification is needed to insure precise work. Another subject requiring investigation is the determination of the degree to which two types of couplings may simultaneously exist in a transducer under test. In most transducers a single type of coupling (e.g., electromagnetic) predominates, but the degree to which other types such as electrostatic, etc., may be present sets a limit to the ultimate accuracy possible in reciprocity calibration.

(b) Develop the self-reciprocity method of calibration especially for measurements in pressure tanks, performance tests at sea, with special attention to tests of production equipment, and for routine tests in manufacturing plants. An important safeguard in the use of self-reciprocity is to ascertain that the transducer used is truly reciprocal. The usual check on this is to use two transducers (not identical) and see if the relation, $e_1/i_2 = e_2/i_1$, is satisfied. Here e_1 is the voltage developed in the first transducer by a current i_2 flowing in the second, and vice versa. In self-reciprocity this check is especially necessary even though only one of the units is to be used in the calibration. A further important check is to determine if the transducer obeys the criteria above at high acoustic pressures as well as low. Still another subject for investigation in connection with self-reciprocity is the properties of the reflecting surface, especially at high frequencies. For calibration at normal hydrostatic pressures the development of an air-baffle type of reflector is recommended.

(c) Develop by theoretical and experimental research the full potentialities of the reciprocity method of calibration in confined media where the impedance of the container must be considered—especially when coated with absorbing layers.

Improved Standard Transducers

(a) Development of standard hydrophones and projectors capable of making the calibration techniques both for relative and absolute calibrations of instruments to an accuracy of better than 0.1 db. This program should include the development of primary standards with high stability with respect to time variations of the properties of the materials of which they are composed; with less than 0.01 db/° C temperature dependence of calibration throughout their useful frequency range; and with flat frequency response throughout their useful range with no sharp variations due to resonances (breakups), the last being checked in every case of pulse technique calibrations. These primary standards need not necessarily have a high response sensitivity but should have a very high signal-to-noise ratio (hydrophone threshold), and should be non-directional.

(b) These primary standards will probably not employ piezo electric crystals because of their time and temperature variations and low

signal-to-noise ratio. Neither can they be electromagnetic or magnetostriction transducers because these instruments, which may have good signal-to-noise ratios, are probably subject to serious time and temperature variations.

(c) The development of electrostatic primary transducers should be carried on because these instruments should have superior characteristics for primary standards to any of the types mentioned in (b) above. While they have the disadvantage of low response (sensitivity) and high impedance, this can be overcome by the development of improved preamplifiers. Electrostatic transducers can be fabricated in any desired shape—in particular, spherical units composed of alternate shells of conductor and dielectric. The electrodes can perhaps make use of evaporation and plating techniques; and for the dielectric, modern polystyrenes, silicones, and titanates are possibilities for investigation.

(d) Development of special primary standards to serve unusual frequency ranges, high hydrostatic pressures, and special measurements. Among the latter may be mentioned the need of a very small absolute standard to measure sound pressure and particle velocity without influencing the sound field near the projector.

(e) Greatly improved secondary standards for field application should be developed. These should have fairly high stability with time and temperature, fairly high response (sensitivity), rugged construction, and reasonably flat frequency response throughout the required range. These can perhaps best be built using ADP crystals or electromagnetic or magnetostriction units. Such secondary standards should be reliable to a small fraction of a db.

(f) Particularly important is the development of projectors more suitable for calibration work than any now available. Work is needed to secure greater stability, and instruments of varying directionality, size, output power, and frequency range should be developed. In particular, a small non-directional projector should be developed for use at short testing distances (one to three feet) for use in the calibration of standards.

Scale Techniques in Calibration

(a) Development of calibration methods, especially free field directivity pattern measurements for *scaled transducers.* These methods will provide rapid measurements to predict the performance of large devices.

(b) Development of scale calibration facilities, especially high frequency pulsing methods, to study the acoustic reflection coefficients of all model targets, including navigational hazards.

(c) An extensive program of theoretical and experimental research into all scaling factors involved in model studies, especially the effects of "re-radiation" if encountered in acoustic model measurements.

Development of Facilities for General Acoustic Measurements

(a) Development of facilities for the final evaluation and acceptance of acoustic materials designed for absorbing coatings, impedance matching units, through-the-hull sound transmission structures, ρc rubbers, antifouling paints, and baffle materials. This will not, in general, require additional measurement systems, but rather adaptations of regular calibration equipment for each specific problem.

(b) Development of calibration methods to include performance evaluation of entire systems including not only acoustic elements, but housings, electronic components, and presentation of information, especially aural presentation. Such over-all calibrations are essential for all echo-ranging systems, listening systems, noise measurement systems, noise producers, and acoustically controlled mines.

(c) Development of methods for calibration

of hull-mounted hydrophones and projectors, this work to concern itself not only with the calibration of the devices themselves, but also to devise instruments and techniques to assist in determining their best location in the hull and proper method of installation of the acoustical elements.

(d) Development of calibration methods for measurements at sea. This should include measurements on surface ship and submarine sonars, and studies of harbor defense systems.

Complex Calibration of Transducers

There is need for the development of a method for measuring phase as well as amplitude relations between pressure and voltage in a transducer. This is particularly important in application of hydrophone response in the measurement of transients.

Improved Measurement and Calibration Tanks

(a) The use of tanks for both calibration and production testing measurements of sonar gear can be greatly extended if better methods are found for the reduction of reflections from the walls and free surfaces. Especial attention should be given to tanks suitable for measurements under large hydrostatic pressures.

The program should have as one of its principal objectives the development of underwater sound *anechoic chambers* corresponding to those available for air acoustics. This should provide absorbing layers for all surfaces, including the free water-air interface. The use of acoustic lenses as a means of beam formation and the elimination of surface reflections should also be included in this general program.

Automatic Operation of Calibration Equipment

(a) Development of directivity measuring equipment for the study of ship-mounted hydrophones and projectors.

(b) Direct recording of response measurements.

(c) Recording impedance bridges.

(d) Development of variable width band-pass filter. This is very useful in measuring the response of a hydrophone to an arbitrary band of noise.

Development of Null Methods of Measurement in Acoustics

Very general studies are needed in this connection. It is probable that increased accuracy will ultimately depend on this type of improvement in measurement technique.

ACKNOWLEDGMENT

Doctors E. L. Carstensen and L. L. Foldy have assisted materially in the preparation of this survey. Mention should also be made of the many others in underwater sound research who gave freely of their advice and ideas on the subject of standards and calibration methods.

APPENDIX: Laboratories Engaged in Underwater Sound Standardization, Calibrations, and Testing

I. Navy Laboratories

1. OFFICE OF NAVAL RESEARCH

(a) *Naval Research Laboratory–Anacostia (Sound Division)*
Location of work: Primarily on barge in Potomac.
Interested people:
H. L. Saxton, Superintendent, Sound Division,
P. N. Arnold, Transducer Section.

(b) *Underwater Sound Reference Laboratory–Orlando, Florida*
Location of work: On lake in vicinity of Orlando, pier and barge plus on-shore laboratories.
Interested people:
O. M. Owsley, Civilian Officer in Charge,
E. L. Carstensen, Physicist, Head of Laboratory Section.

2. BUREAU OF ORDNANCE

(a) *Naval Ordnance Laboratory–Washington*
Location of work: Primarily at Barcroft Reservoir, Virginia and White Oaks, Maryland Laboratory.
Interested people:
A. V. Atanasoff, Acoustics.

3. BUREAU OF SHIPS

(a) *Navy Underwater Sound Laboratory–New London, Connecticut*
Location of work: Primarily barge in Thames River, also some lake work.
Interested people:
John Ide, Technical Director of Laboratory.

(b) *Navy Electronics Laboratory – San Diego, California*
Location of work: Barge in bay, barge in Sweetwater Reservoir near San Diego.
Interested people:
Captain Rawson Bennett, Director; C. J. Burbank, in charge of Measurement Section.

4. DAVID TAYLOR MODEL BASIN
Location of work: Towing Basin, Carderock, Maryland.
Interested people:
V. L. Chrisler, Chief, Sound Division

II. Navy-Sponsored Research and Development

1. ACOUSTIC LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Location of work: M.I.T. Acoustic Laboratory, Cambridge, Massachusetts.
Interested people:
R. H. Bolt, Director of Acoustic Laboratory; L. L. Beranek, Associate Director; R. L. Fay, Director of Special Project.

2. WOODS HOLE OCEANOGRAPHIC INSTITUTION, WOODS HOLE, MASSACHUSETTS
Location of work: Laboratory and ship, Woods Hole, Massachusetts.
Interested people:
C. O'D. Iselin, Director.

3. ORDNANCE RESEARCH LABORATORY, PENNSYLVANIA STATE COLLEGE
Location of work: Black Moshannon Lake Laboratory and acoustic testing at sea.
Interested people:
E. A. Walker, Director; L. Miller, in charge of Moshannon Laboratory.

4. MARINE PHYSICAL LABORATORY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO, CALIFORNIA
Location of work: Navy Electronics Laboratory, Point Loma, California.
Interested people:
C. Eckart, Director.

III. Industrial Laboratories

1. BRUSH DEVELOPMENT COMPANY, CLEVELAND, OHIO
Location of work: Acoustic testing tank in factory.
Interested people:
A. L. W. Williams, President, H. Miller, Head of Acoustic Development.

2. SUBMARINE SIGNAL COMPANY, BOSTON, MASSACHUSETTS
   Location of work: Tank in factory and barge in Boston Harbor.
   Interested people:
   L. Batchelder, Engineer.

3. RADIO CORPORATION OF AMERICA, PRINCETON AND CAMDEN, NEW JERSEY
   Location of work: Barge in river at Camden, New Jersey, and lake at Princeton laboratory, also tank in Camden laboratory.
   Interested people:
   H. F. Olson, Director of Acoustics Research.

4. GENERAL ELECTRIC COMPANY, SCHENECTADY, NEW YORK
   Testing arranged by Navy Department.

5. WESTINGHOUSE ELECTRIC COMPANY, WARREN, PENNSYLVANIA
   Testing arranged by Navy Department.

6. SANGAMO ELECTRIC COMPANY
   Location of work: Testing at New London Laboratory.
   Interested people:
   C. H. Lamphier, Vice-President,
   W. W. Sherwood, Chief Engineer.

7. WALLACE-TIERNAN, BELLEVILLE, NEW JERSEY
   Location of work: Tank in laboratory.

CHAPTER 3

1. INTRODUCTION

2. UNDERWATER SOUND RANGE

3. SUMMARY OF DATA ON UNDERWATER AMBIENT NOISE

4. RECOMMENDATIONS FOR FUTURE MEASUREMENTS OF AMBIENT NOISE

SUGGESTED PROCEDURES

SUPPLEMENTARY OBSERVATIONS

HYDROPHONE CALIBRATION

ADDITIONAL MEASUREMENTS NEEDED

ANGULAR DISTRIBUTION OF NOISE FIELD

RAIN AND HAIL

WATER NOISE

MARINE LIFE

SHIP NOISE

5. RECOMMENDATIONS FOR FUTURE MEASUREMENTS OF UNDERWATER SOUNDS FROM SHIPS

Ambient Noise and Sounds from Ships

VERN O. KNUDSEN AND LEO P. DELSASSO
University of California at Los Angeles

1. INTRODUCTION

An examination of existing sources of information reveals that there is a large amount of data on underwater sounds that have been obtained by Naval and civilian research groups in the United States, Canada, and Great Britain. The purpose of the survey reports was to collect, analyze, and evaluate all available data in the audible and ultra-audible ranges, to reduce to the same scale of measurement all data which appeared to possess practicable utility, and to compile the selected data in such a way as to make them useful to those groups engaged in research, development, and design in the fields of underwater sound.

The original data from investigations on underwater sound are usually detailed and specific. It was found possible in many cases to condense and combine them with similar data from other sources, and thus arrive at results that reveal the ranges and the most probable values of ambient noise, sounds from ships, and other noise generators.

The above survey report on ambient noise is very useful in its present form. There are some gaps in the data, however, that should be filled. When these gaps are filled, in accordance with some specific recommendations submitted later in this report, it will be possible to predict the ambient noise in open water by means of certain oceanographic observations, such as wave height, wind, and other factors which influence the breaking of waves at the ocean's surface. In general, it is not possible to predict ambient noise levels in harbors and coastal waters, although the above survey report gives the probable values in many locations. It usually will be necessary, however, to make measurements in specific locations under conditions that will be typical of those prevailing when existing or new apparatus is used in such waters.

Basic research should be undertaken to reveal detailed scientific knowledge of how sound is produced in water by surfaced and submerged ships, and by all natural causes, at all water depths of practical interest. This knowledge would be helpful in interpreting and extending underwater sound measurements on actual ships, and possibly even in predicting the sound output from new types of propulsive or other equipment. Although some basic research progress along these lines already has been made, revealing, for example, that ship sounds are largely produced by cavitation at the propellers, there is as yet no quantitative theory as to how these sounds are produced. It is imperative that better and more knowledge be obtained regarding the dependence of cavitation noise on hydrostatic pressure (or depth of submergence). Further, there is no theory on the nature of the production of deep-sea ambient noise; there is a paucity of information as to the existence of such noise, from marine life or of physical origin.

There are a number of features that are common to any program of measurements of ambient noise and sounds from ships. These will be considered first, and then separate sections will be devoted to (1) ambient noise, and (2) sounds from ships.

2. UNDERWATER SOUND RANGE

Somewhere between the "super-laboratory" and a rowboat there is a feasible facility for measurements of ambient noise and sounds from ships. After careful consideration of this problem, including visits to the various ranges that were operated during World War II by the United States, Great Britain, and Canada, and recent conversations or correspondence with existing U. S. Naval agencies interested in underwater sounds, it seems to us that the optimum choice is a well equipped and adequately staffed laboratory ship. Such a ship might well have a "home base" where water and weather conditions are favorable and where certain supplementary equipment (as planted hydrophones and appropriate associated sound recording apparatus in a suitable hut) is permanently installed. The "home base" should be located in a sheltered position on deep isothermal water. In addition, the location should be relatively free of fog and not too distant from open sea. This equipment at the home base should serve the purposes of (1) giving a continuous record of ambient underwater noise from one or more hydrophones permanently located in deep, open water, and (2) determining the sound spectra of the auxiliaries on surface ships and submarines and also the composite sounds from ships as they cruise along a course over the planted hydrophones at typical speeds and operating conditions.

The design of the apparatus should be such as will provide records that may be readily interpreted. This is particularly important since at present and for some time to come trained personnel for reducing data are not and will not be available. Every effort, therefore, should be made to make such equipment as automatic as possible. To this end multiple indicating and recording acoustic spectrometers should be provided. Such equipment as was used in the last war should be considered as a starting point. In addition, apparatus for giving both short-time and long-time averages should be developed. Prior to the actual construction of any of these facilities a thorough study of methods of analysis, such as is now under way at the Marine Physical Laboratory and the Navy Electronics Laboratory at San Diego, should be investigated.

3. SUMMARY OF DATA ON UNDERWATER AMBIENT NOISE

Figures 1, 2, 3, and 4 provide a compact summary of what is now known about the magnitudes and spectra of underwater noise. Figure 1 gives average sound spectra for water noise as a function of sea state and wind velocity. The ordinates for the curves in Fig. 1 give the average sound pressure level in a band one cycle wide, referred to a pressure level of 0.0002 dynes per square centimeter. It will be noted (1) that the pressure level is a function of the sea state or wind velocity (the over-all pressure level in a band from 100 c.p.s. to 10 kc increases from about 57 db in a "calm sea" to about 83 db in a sea under a wind of 35 m.p.h.), and (2) that the spectrum level decreases with increasing frequency at a rate of about 5 db per octave. The standard deviation of the noise levels given in Fig. 1 is of the order of 4 to 5 db. Instantaneous peak levels about 10 db above the average levels given in Fig. 1 are of frequent occurrence; they need further investigation.

Figure 2 gives the sound spectrum for croaker noise during a period of high activity

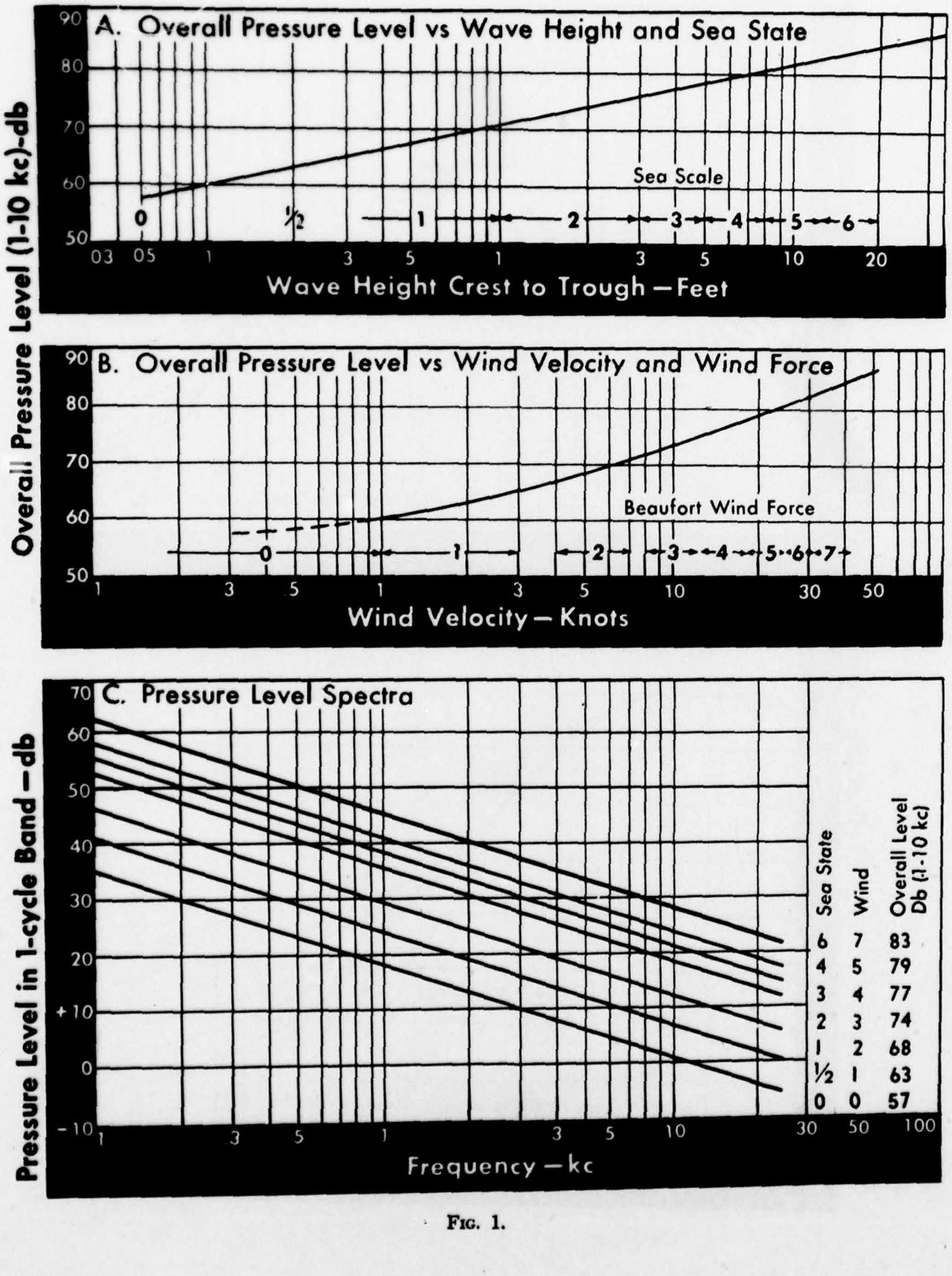

A. Overall Pressure Level vs Wave Height and Sea State
Sea Scale
Wave Height Crest to Trough—Feet
B. Overall Pressure Level vs Wind Velocity and Wind Force
Beaufort Wind Force
Wind Velocity—Knots
Overall Pressure Level (1-10 kc)-db
C. Pressure Level Spectra
Pressure Level in 1-cycle Band—db
Frequency—kc
Sea State
Wind
Overall Level Db (1-10 kc)
6 7 83
4 5 79
3 4 77
2 3 74
1 2 68
½ 1 63
0 0 57

FIG. 1.

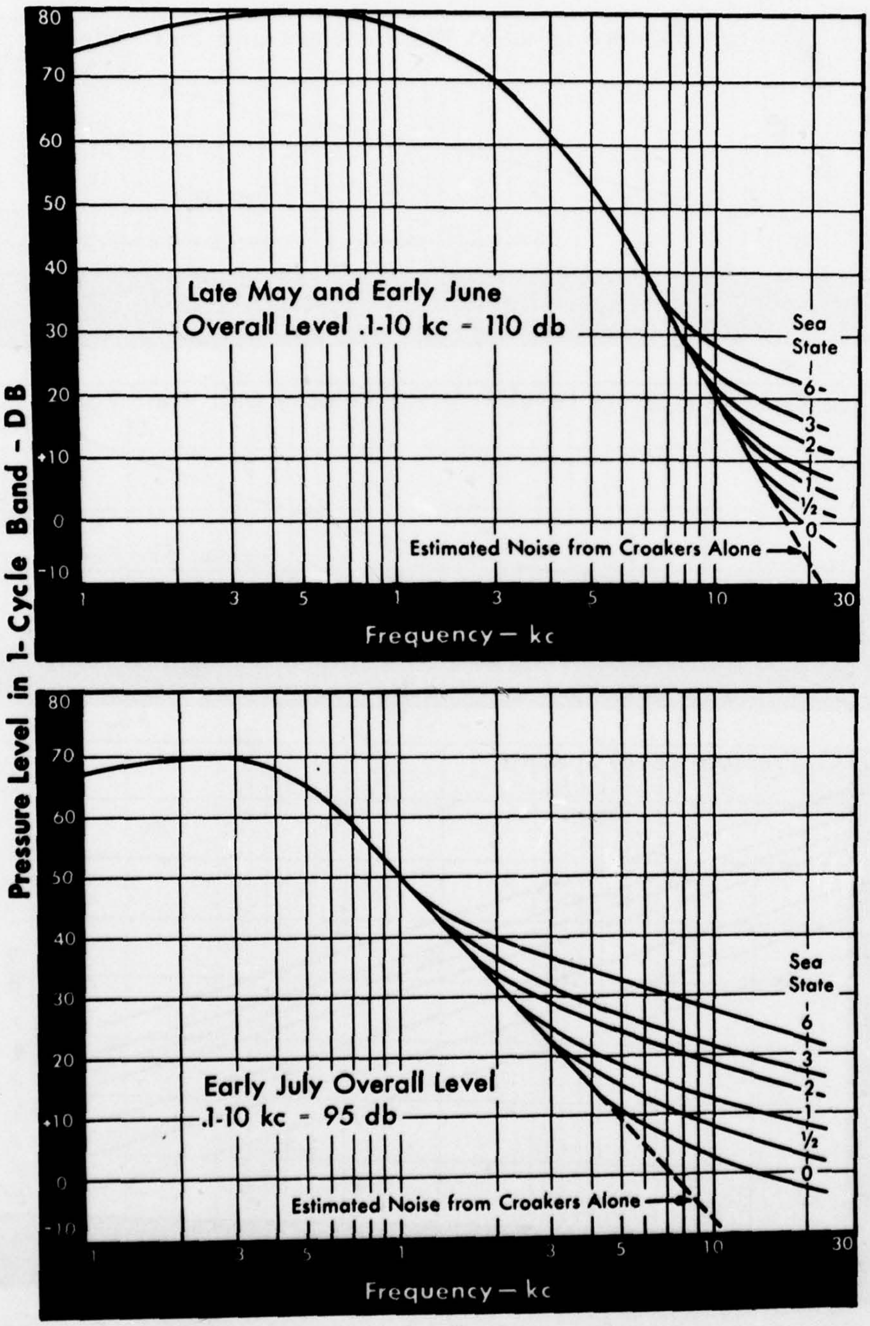
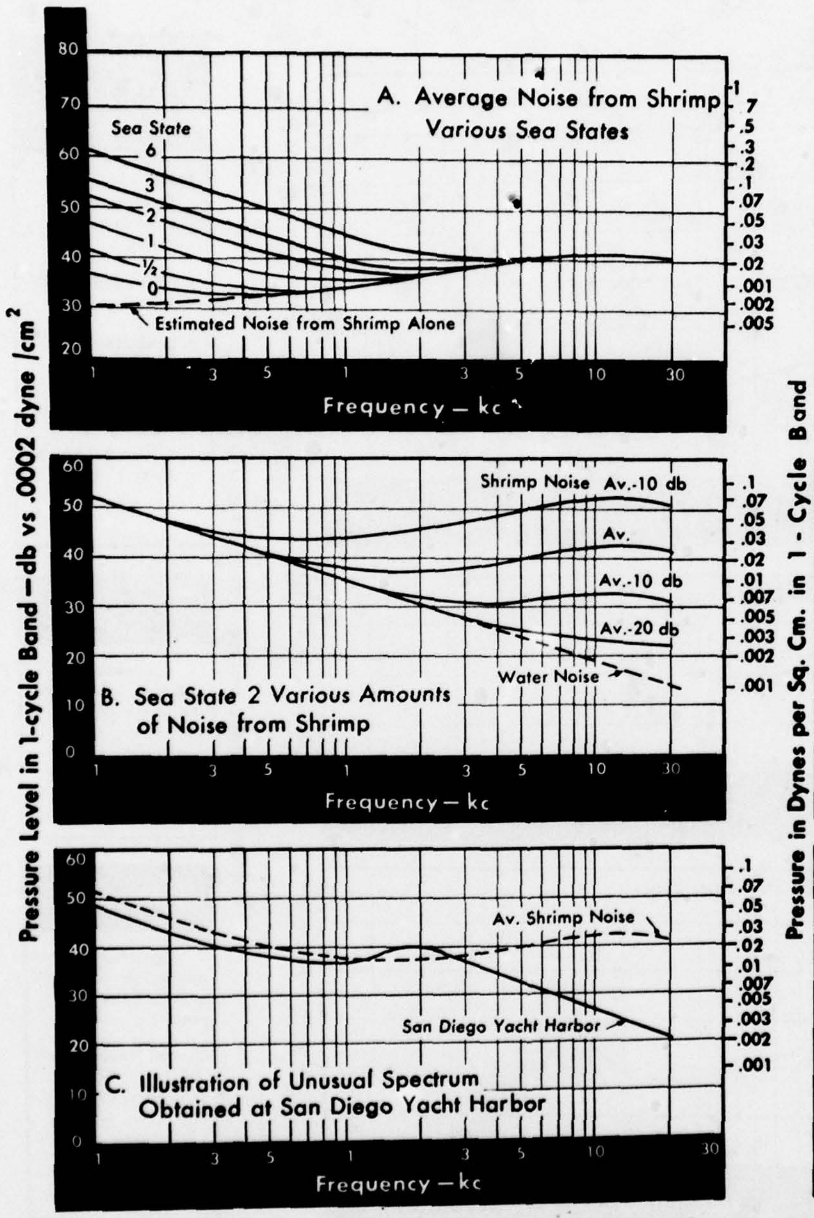

Pressure Level in 1-Cycle Band - DB
Late May and Early June
Overall Level .1-10 kc = 110 db
Sea State
6
3
2
1
½
0
Estimated Noise from Croakers Alone
Frequency — kc
Early July Overall Level
.1-10 kc = 95 db
Sea State
6
3
2
1
½
0
Estimated Noise from Croakers Alone
Frequency — kc

FIG. 2.



Overall Pressure Levels

Sea State	Overall—db .1-10 kc	Overall—db .3-10 kc
0	79.5	79.5
½	79.5	79.5
1	80.0	79.5
2	80.5	80.0
3	81.0	80.5
6	84.5	82.5

Overall Pressure Levels

Shrimp Noise	Overall—db .1-10 kc	Overall—db .3-10 kc
Av.-10	89.5	89.5
Av.	80.5	80.0
Av.-10	75.0	73.0
Av.-20	74.0	71.0

Overall Pressure Levels

Curve	Overall—db .1-10 kc	Overall—db .3-10 kc
......	80.5	80.0
......	76.0	75.0

FIG. 3. Pressure level spectra of ambient noise in the presence of snapping shrimp.

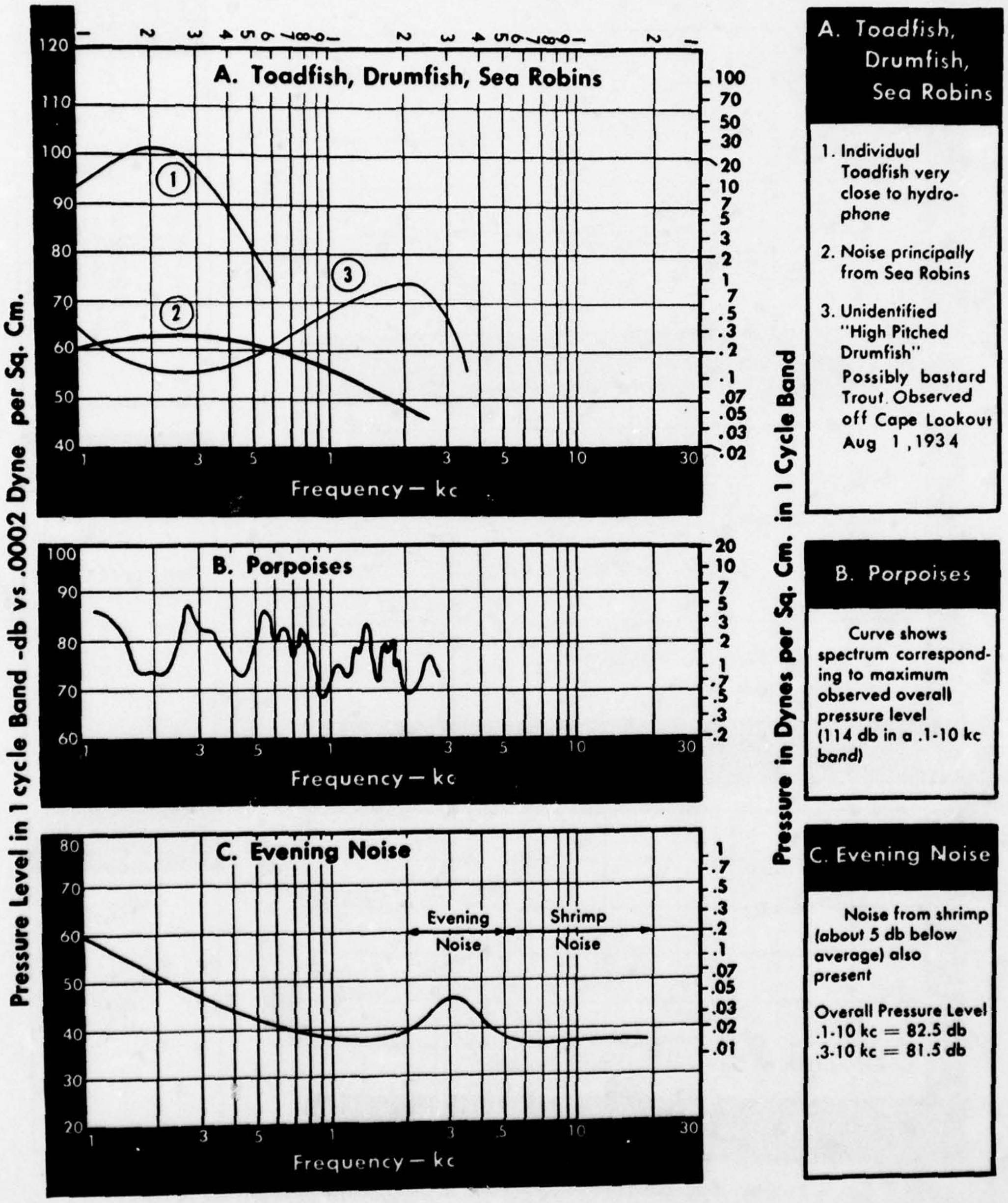


FIG. 4. Illustration of ambient noise spectra in the presence of miscellaneous marine life.

of croakers. The curves show the over-all effect of the croaker noise combined with water noise corresponding to the indicated sea states. It will be noted that the croaker noise completely predominates over the water noise at low frequencies. At very high frequencies, however, the water noise is the controlling factor.

Figure 3 gives some average sound spectra in waters in which shrimp noise is present. It will be noted that at low frequencies the water noise is predominant, whereas at high frequencies the shrimp noise predominates.

Figure 4 gives the spectra for the sounds of several forms of soniferous marine life. Each sound spectrum corresponds to the noise recorded near each marine animal. These sounds would, of course, be greatly attenuated at greater distances from the sound source.

4. RECOMMENDATIONS FOR FUTURE MEASUREMENTS OF AMBIENT NOISE

Data such as are summarized in Figs. 1 to 4 give a reasonably complete qualitative and quantitative description of ambient noise in typical waters. However, it is not possible to predict from the available data the noise conditions to be expected in all possible waters. In many locations, satisfactory data on ambient noise can be obtained only by means of local surveys. In conducting any further work of this nature, it would be desirable to follow procedures that will have the greatest value in supplementing the existing data on ambient noise. The sections that follow discuss the recommended procedures and the types of additional data required.

Suggested Procedures

Although satisfactory procedures were developed and followed in many of the surveys conducted during the latter part of World War II, in future work two items should receive further attention.

Supplementary Observations

Observations of wind velocity, wave height, weather conditions, water temperatures, salinity, bubbles and suspended material, bottom conditions, water depth, and similar information will be valuable in the interpretation of ambient noise data and should be continued as an important part of all noise surveys. It will be desirable to make additional observations on the character of the waves, such as period, length, steepness, number, and the prominence of whitecaps. Such observations will be helpful in deriving a more precise relation between water noise and sea conditions. Additional information concerning the possible dependence of water noise on depths below the surface might be obtained by the use of a buoy recording unit, containing a hydrophone, an amplifier, and a recorder that would indicate time, depth, and sound pressure level. Such a recording unit, which would be largely automatic, could contain suitable diving apparatus that would go down slowly to any desired depth, remain at this depth for a predetermined time, and then rise to the surface. The time-position path of the diver might be determined by means of methods that were developed during World War II.

Hydrophone Calibration

There is evidence that some discrepancies in the available information are attributable to differences in hydrophone calibration. Particular attention should be paid to the proper calibration of hydrophones that are asymmetrically directional, such as are usually employed in underwater sound work. This requires a knowledge of the distribution of the noise field, as well as the calibration of the hydrophone at as many frequencies and angles of orientation as are required to provide a suitable correction for directionality. It would be helpful to make a direct comparison, in the noise field, of the response of directional and non-directional hydrophones. There is need for

non-directional microphones operating at very high frequencies.

Additional Measurements Needed

Angular Distribution of Noise Field

The distribution of water noise is presumed to be isotropic. If feasible, this presumption should be checked by measurements in deep water, with a highly directional hydrophone at different orientations in vertical and horizontal planes. Measurements of other types of noise with a directional hydrophone may also prove to be useful. For example, the location and extent of colonies of marine life can probably be determined more readily with a directional than with a non-directional hydrophone.

Rain and Hail

Practically no information is available at present on this noise source. The principal difficulty in obtaining this information arises in obtaining comparable data with and without rain or hail. Brief showers will present the best opportunity for obtaining such information. Measurements should be made in a sea of state 1 or less and at locations free from the sounds of marine life.

Water Noise

The correlation between water noise level and wind or sea is not entirely satisfactory (standard deviation of 5 db). It seems likely that a better correlation might be obtained if other information on wave characteristics such as period, length, or steepness were available. This might be supplemented by more quantitative data on the state of the sea surface—for example, by photographs of the sea surface, by measurements of the wind velocity at a small, fixed height above the sea surface, and by wave measurements with some of the newly developed wave meters. Improvement might also result from an investigation of multiple correlations. For example, with sufficient data it might be possible to classify the information first by sea state and then for each sea state derive a relation between noise level and wind force. Thus there would result a family of curves relating noise level to wind force, each curve applying to a particular sea state. This would probably result in a relation with errors of estimate considerably smaller than a relation based on either variable alone.

There are relatively few available measurements of water noise in seas of state 4 and higher. Further work should be directed toward obtaining reliable measurements in rough deep water. Similarly, almost nothing is known about possible noises (from icebergs, ice flows, etc.) in arctic waters. Oceanographic as well as acoustical data are needed. Melting and freezing give rise to extreme temperature gradients which greatly affect all acoustical phenomena in these waters.

Marine Life

Further investigation of the noise produced by croakers will probably be desirable since the areas inhabited by these fish and the noise magnitudes to be expected cannot at present be mapped with any certainty. Observations in warm waters should be carried out over a 24-hour period and repeated several times a year in order to detect the presence of other possible types of noise-producing marine life, (e.g., the "evening noise" reported near certain Pacific islands). All soniferous marine animals should be identified, their habits studied, and sound-making mechanisms determined.

Ship Noise

When additional measurements are made in regions with prominent ship noise, an attempt should be made to correlate the noise data with other information, such as number of ships, their size and speeds, distances from measuring station, etc.

5. RECOMMENDATIONS FOR FUTURE MEASUREMENTS OF UNDERWATER SOUNDS FROM SHIPS

As in the case of ambient noise measurements, there is evidence that some of the large deviations are attributable to differences in hydrophone calibration. With the calibration experience and equipment now available, future measurements should be free from errors of calibration of hydrophones and other parts of the measuring apparatus. The large deviations in ships' noises requires further statistical study. In spite of the high dispersion of the data on sounds from ships, it is desirable to know the values of the statistical fluctuations with considerable precision.

Complete descriptive data on the ships measured are essential to the proper interpretation and use of the observed sound levels. The recorded data should include the number, diameter, pitch (and slip), and r.p.m. of propellers; the displacement tonnage (normal and at time of test); the condition of the ship (as to fouling, damaged parts, etc.); the speed of the ship during the test and also the maximum speed, and the water speed as well as all other relevant water conditions.

The measurement of sounds from ships at points near but external to the vessel in shallow water is a relatively simple matter. Although much information of this nature has already been gathered, the interpretation of such measurements is very difficult since the effect of such factors as bottom impedance reflections and placement of the hydrophone must be taken into account. It would be helpful to be able to fix the parameters describing the bottom impedance in such a way that one could estimate the influence of these parameters on the sound pressure levels of the ships' noise in the various frequency bands of practical interest. The classification of the bottom impedances in shallow waters is of considerable importance. On the other hand, measurements taken in very deep water are more readily interpreted, but the measurements themselves are usually difficult. Facilities should be provided for making both types of measurement.

In deep water several types of routine and special measurements should be made. One of great importance is the self-noise of the vessel as measured through its own transducers and by auxiliary quiet hydrophones attached to the vessel. A second type of measurement requires the pick-up hydrophone to be submerged at various depths. In previous work this has been done by supporting the unit from a small buoy some distance from the measuring ship. Where records are to be taken over a long period of time some sort of buoy technique seems more feasible. In all such measurements it is essential to know the range and bearing of the sound source from the microphone as a function of time.

Research on the reduction of sounds from ships should give special attention to hydrodynamically as well as machinery-induced vibrations in the ship's structure. Several agencies are engaged in the investigation of special phases of this problem, but there is need for over-all planning and proper coordination of the necessary research. Further coordinated studies of the origin of ships' noises should be made for the purpose of determining and evaluating the individual sources of noise. For example, how much does the motion of the hull (as determined by towed experiments) contribute to the noise, and how much does the propelling mechanism contribute?

Some of the acoustical investigations recommended herein are already underway, or soon will be, under the auspices of the various laboratories. Many of the recommendations are based on information received by the authors from these laboratories. To those who cooperated in furnishing such information, the authors express their thanks and appreciation.

CHAPTER

4

1. PRESENT STATE OF KNOWLEDGE

2. FUTURE RESEARCH

Transmission and Scattering of Underwater Sound

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Brown University
AND
HECTOR F. WILLIS
British Admiralty Research Laboratory

SUMMARY

The survey is in two parts. Part 1 reviews briefly the present state of knowledge of underwater sound transmission and scattering under the following section heads: absorption of sound in the sea; mirror effect; refraction; sound channels; shallow water transmission; bottom, surface, and volume reverberation. Refraction appears to be the topic which has received greatest attention so far, with reverberation a close competitor. The general results of the interpretation of available data in terms of the ray theory are discussed. Reverberation is treated similarly with some emphasis on the gaps in present knowledge.

Part 2 (the larger portion of the report) presents detailed recommendations of future research. The following points are particularly emphasized:

(1) The desirability of further pure research to enlarge the reservoir of basic knowledge from which alone future fruitful applications and developments of underwater sound can come.

(2) Recommendation of a world-wide survey of sonar conditions to increase the supply of available data from widely different oceanographic localities.

(3) Recommendation of model scale experiments under laboratory-controlled conditions for deducing the consequences of transmission theories under circumstances too complicated for mathematical analysis.

(4) Recommendation of more extensive theoretical and experimental studies of sound absorption in sea water.

(5) Recommendation of further study of the microstructure of the sea.

(6) Recommendation of further study of the sea bed.

(7) Recommendation of further research on scattering, particularly by model technique, with a view to reducing reverberation or more effectively accounting for it.

1. PRESENT STATE OF KNOWLEDGE

Introduction

The propagation of sound from a transmitter of finite size located in an infinite homogeneous water medium is well understood. Except at very short ranges the intensity in any direction falls off inversely as the square of the range,

R, and is further modified by an exponential attenuation factor resulting from absorption of the sound. The intensity then has the form

$$I = I_0 e^{-\alpha R}/R^2,$$

where α is the absorption coefficient for intensity. The distribution of intensity over various directions is calculated from the properties of the transmitter, leading to the incorporation of a directionality factor in the expression for I.

Transmission in the sea, however, does not conform to this simple picture. In the first place the presence of the sea surface affects the transmission, often to a considerable extent. If this surface is assumed to be plane, its presence can be taken into account by the introduction of an image transmitter of opposite phase above the surface. Usually, however, this procedure is not valid, because the surface is not plane, but disturbed by the presence of waves. In relatively shallow waters the bottom of the sea introduces another and more troublesome boundary condition, because of our uncertain knowledge of the character of the sea bed. Like the sea surface, the bottom is not usually plane, but is liable to possess undulations. Moreover, bottoms vary markedly in their reflecting and absorbing power. Even the sea water itself is far from being the homogeneous medium considered in the first paragraph; it shows frequent temporal and spatial variations in velocity including broad variations with depth, together with smaller variations from point to point in the same or different horizontal planes. It also contains foreign matter in the form of animal and plant life, bubbles, etc.

Absorption of Sound in the Sea

Unless we are quite sure how much sound intensity is lost by absorption through the water as a stationary homogeneous fluid, it is difficult to theorize on the modifications to be expected from such perturbing influences as surface and bottom reflections, scattering, temperature fluctuations, etc. It has, therefore, been important to determine the true attenuation introduced by the passage of the sound beam through the body of the sea. This is a difficult problem. The absorption coefficient at sonar frequencies is sufficiently small to make it difficult to measure its value without considering an expanse of sea which necessarily introduces the other complicating factors to some extent. However, a considerable number of measurements are available from various sources. The consensus of many observers is that the minimum value of the absorption coefficient in the absence of disturbances due to refraction, surface state, etc. is in many cases approximately 4 db/kiloyard at 24 kc. With regard to frequency dependence, certain work suggests that under minimal absorption conditions around 24 kc the coefficient is roughly proportional to the frequency raised to the 1.4 power.

Recent measurements by the decay method in the reverberation sphere indicate that for bubble-free sea water at 22 kc the upper limit of the absorption coefficient is about 6 db/kiloyard. The true value is probably lower, but not below 4 db/kiloyard. Artificial sea water (NaCl solution with concentration 30 parts per thousand) yields about 4 db kiloyard at 22 kc and tap water about 3 db/kiloyard.

The very long ranges encountered in the use of SOFAR and the successful interpretation of shallow water low frequency transmission in terms of normal modes suggest strongly that the absorption coefficient in the audible range is very much lower than the figures of the preceding paragraph. No precise values are available but a rough upper limit of about 0.04 db/kiloyard is indicated for the range from 10 to 1,000 cycles.

Reasonably reliable figures have been obtained by several different methods for fresh water at high frequencies (1 mc and above). Here the absorption is sufficiently large to

permit fairly accurate laboratory measurement. The results indicate that the absorption coefficient varies as the square of the frequency over a wide range (1 to 50 mc), so far agreeing in functional dependence with the Stokes shear viscosity theory of absorption. However, the actual observed values are considerably in excess of the theoretically computed ones. The reason for this is still a subject of investigation, though it now appears probable that most of the discrepancy can be attributed to structural relaxation. This is further commented on in the section in Part 2 of this Report entitled "Absorption of Sound in the Sea."[2] In this connection it is of interest to note that the observed absorption coefficient of fresh water at 20° C and 1 mc is about 177 db/kiloyard. This compares with a value of 300 measured in the open sea under similar conditions. On the other hand, if we were to assume that the inverse square frequency dependence holds also in the kilocycle range with the same value of the parameter α/v^2 (45×10^{-17}cm^{-1}sec.^{2}), the value of α at 24 kc would be about 0.1 db/kiloyard, which is some 50 times smaller than the observed value in sea water. It seems clear that the mechanism of absorption at lower frequencies is an important subject for further study.

A recent review of measured absorption values by Eckart indicates that in fresh water (lake water) α at 0.69 mc comes out by a transmission method to be 45 db/kiloyard, about what one would expect from the figures mentioned above. This also checks with the Fox and Rock value for fresh water at 50 mc of 2,000 db/kiloyard.

Mirror Effect

We consider now the problem of transmission in deep water, taking account of the surface of the sea but neglecting the bottom. When the surface is flat and the water homogeneous, the sound intensity at various ranges should show the characteristic interference pattern associated with "Lloyd's mirror." In practice such patterns have been observed at frequencies of the order of 200 cycles, but less readily at higher frequencies, and then only if the surface of the sea is very calm. They are rarely obtained at frequencies of the order of 20 kc, except for a very quiet sea, though the presence of an inherent pattern may sometimes be brought out by a statistical analysis of a large number of observations. Disturbances of the surface of the sea may be expected to mask the interference pattern, though this wiping out of the pattern in practice seems larger than can be attributed entirely to this cause. It seems likely that nonhomogeneities in the sea itself may be a contributory factor.

Refraction

The hitherto simple problem of wave propagation becomes difficult as soon as we try to take account of velocity variations. The most significant variations occur with depth, the sound velocity tending to be a function of depth only. Horizontal variations, though undoubtedly present, are much less stable and appear to be of smaller significance. Vertical variations of sound velocity produce a "refraction" of the sound beam, which may be vital for the effectiveness of sound transmission. An exact treatment of refraction by wave analysis has been achieved only in special cases, e.g., for a velocity variation with depth of the form $v = v_0/(1 + By)$. However, a simple approach to the problem has been obtained by the development of the method of *ray acoustics.* High frequency sound, like light, can be imagined to be propagated in the form of rays, and the paths of these rays are easily calculable in terms of the known velocity gradient. The plotting of the various rays of sound emerging from the transmitter then gives a picture of the distribution of sound intensity throughout the medium. It has even been possible to put the process on a quantitative basis by interpreting

the sound intensity in terms of the concentration of rays at a point, much as an electric field intensity may be expressed in terms of the density of lines of force.

Research has also been carried on concerning the nature of the observed velocity gradients in the sea. In many cases the velocity changes appear to be primarily due to temperature changes at different levels. This has led to the development of the "bathythermograph," a very simple and robust instrument for recording the variation of the temperature with depth for any part in the sea. Neglecting variations in salinity, and taking into account the known increase in velocity with pressure in the ocean, it then becomes possible to construct the corresponding velocity-depth variation.

The study of many such records has served to establish certain general features of sound velocity variations in the sea. All records can be grouped into a small number of types according to the different ways in which the propagation of sound is affected near the surface of the sea.

The first type occurs when the velocity of sound is reasonably uniform in the surface layers. The second type corresponds to cases where the velocity increases noticeably with depth in the surface layers (a rather uncommon situation). The third type corresponds to the opposite case of a sharp negative velocity gradient near the surface. A fourth group covers many cases of negative gradient which are intermediate between the first and third types.

The ray theory reaches certain conclusions concerning the propagation of sound in these various velocity gradients. Generally speaking, sound should be propagated in a reasonably normal manner in the first type field if we confine the transmitter and receiver to the surface layers. A field of the second type should result in a concentration of energy in the surface layers, and so should be very favorable to long distance transmission. Unfortunately, there is little experimental evidence on this point, though what exists is favorable to the theory. A third pattern, on the other hand, should produce a sharp downward refraction of the sound beam, and here it is possible to predict a boundary beyond which there should exist no intensity of sound (the shadow zone).

In many cases the velocity is reasonably uniform down to a certain depth and then falls very quickly to a lower value. The layer of transition is called the "thermocline." It should result in a splitting of the sound beam sent out by a transmitter, part of the sound being propagated horizontally in the isothermal water at the surface, the rest being sharply refracted downwards as a distinct beam, leaving a region of shadow between the two. The ray theory leads to the expectation that the field intensity should fall abruptly as we go beneath the thermocline (layer effect due to spreading of the rays).

Many measurements have been made of the intensity of sound transmission at various depths and at various ranges from a source, and the sound fields so plotted have been compared with calculations based on simultaneous thermal measurements. Generally speaking, there has been fair qualitative agreement between theory and observation, but the quantitative agreement has been less good. In certain cases the theoretical description of the sound field has been brilliantly confirmed in practice, but in other cases certain characteristic predictions, such as the split beam effect, have been unaccountably masked. Such failures may be due to the fact that the temperature gradient is never quite the same throughout the same horizontal plane, and in any case is always liable to vary appreciably during the course of a single experiment. Thus ray plotting can rarely be expected to be a very accurate process. From a more fundamental point of view it seems clear that the propagation of sound in the sea is determined by other

factors besides simple refraction, and that the refraction has to be large to be the dominant factor.

The ray theory of sound propagation in water cannot be expected to provide a complete description. It is only an approximate mathematical approach, whose reliability decreases considerably at lower frequencies. In particular, the ray theory predicts zero intensity in the shadow zones, whereas sound is certainly detected there, even though with considerably less intensity than in the main beam. This, however, is a limitation of the mathematical approach, and not necessarily of the hypothesis of refraction. In the special case of downward refraction (mentioned at the beginning of this section), where it is possible to carry out a rigorous calculation it has been found that some sound intensity is to be expected in the shadow zone, though this intensity is still significantly less than that normally observed in practice.

The ray theory leads one to expect considerable attenuation in the passage of sound from a transmitter above the thermocline to one below it. A fair degree of attenuation has certainly been observed in practice, though not as much as was expected from the theory.

Sound Channels

Ray refraction theory leads to the conclusion that if the sound velocity has a minimum value at a particular depth, sound emitted by a source at this depth will tend to concentrate in a horizontal plane at this level. Provided the natural attenuation is small, sound can therefore be propagated to a very considerable distance along such a "channel."

Since the surface layers of the sea are usually warmer than those farther down, the velocity of sound normally decreases with depth for the first few hundred feet. But at depths of several thousand feet the increasing hydrostatic pressure causes the velocity ultimately to rise indefinitely. The result is a fairly broad sound channel at a depth of several thousand feet, known as the SOFAR channel. The propagation of explosive waves along this channel has proved remarkably successful. The explosions have been detected at ranges of several thousand miles, and the character and timing of the signals recorded have agreed well with the predictions of the refraction theory.

It is not inappropriate here to remark that explosive sounds have already proved useful as an aid to acoustic research in the sea. Thus the very short pulse length of such sounds implies the possibility of separating out on reception, by their different arrival times, the directly transmitted sound from that reflected from surface and bottom and that scattered in various parts of the medium. This is usually very difficult with the longer pulse lengths of sound produced by the standard transducer. The very short pulse of explosive sound has a correspondingly great frequency spread which enables the frequency dependence of reflection at the bottom to be studied with particular convenience.

Refraction at Low Frequencies

The considerations of the section entitled "Refraction" apply mainly to the high frequency region where the ray theory is applicable, and the experimental verifications have been carried out mainly at 24 kc. Much less work has been done on the refraction of sound at low (sonic) frequencies. However, preliminary investigations have been made over a frequency range from 0.2 to 22.5 kc under various conditions of refraction. At the lower frequencies the measured intensities show variations with range which are clearly influenced by the Lloyd mirror effect. A detailed calculation, assuming mirror reflection and taking account of the varying velocity of the medium, gives an interference pattern dependent on the refraction, and agrees well with the experimental results. Re-

sults are less satisfactory at the higher frequencies where the mirror effect becomes progressively less operative.

Shallow Water Transmission

The transmission of sound in shallow water where the sea bed must be considered provides a more difficult problem. The sea bed can vary considerably in its reflection and scattering properties. On the one hand, some types of soft mud bottoms reflect so little sound at ultrasonic frequencies that the problem is much the same as that in very deep water. On the other hand, a soft mud bottom containing large quantities of air bubbles will reflect a large fraction of the incident sound. A hard sand bed may reflect 50 percent or more of the incident sound intensity and so considerably modify the propagation of the beam. The results reported so far indicate that bottom reflection is a very complicated matter. One of the difficulties is doubtless the failure to make use of a more precise characterization of the properties of the bottom.

As might be expected, the bottom of the sea lends itself to successful mathematical treatment primarily at low frequencies. Success has been achieved in dealing with the propagation of sound of the order of 200 cycles in a layer of isothermal sea water bounded on the top by a plane pressure-release surface, and on the bottom by the plane surface of a medium with properties different from sea water but still considered as fluid. This definite mathematical problem has been solved rigorously in terms of the normal modes of vibration of the system, and the distribution of sound intensity has been found to agree well with measurements carried out at 200 cycles in shallow water. Earlier attempts to base a theory of propagation on the assignment to the sea bed of a certain acoustic impedance yielded results differing seriously from experimental values. Only when the sea bed was assumed to behave as a second fluid with appropriate acoustic resistance was it possible to account for the observed propagation effects. The propagation of low frequency sound in shallow water as interpreted by this theory presents a close parallel with the propagation of electromagnetic waves in a wave guide.

In principle, the theory outlined above is applicable also to high frequencies, but here we expect to have to take into account unevenness in the surface and bottom preventing the latter from functioning as plane boundaries. This is a difficult problem, made more so, of course, by the large number of simultaneously existing normal modes at high frequency.

Recent work by Raitt in California on the reflection of 18-kc vertically directed sound by the sea bottom indicates that at this frequency the water-bottom interface scatters sound diffusely. To explain his results it is not necessary to assume penetration of the bottom by the sound. In fact, the results appear to provide definite evidence against penetration to more than a few yards.

The many observations on high frequency propagation in shallow channels seem to fit reasonably well a simple formula based on an approximate approach. In the case where the sound is refracted downwards it will be propagated forward after reflection from the sea bed, and may, in fact, reach a distant point after a number of cycles of downward refraction and upward reflection. In terms of the number of such cycles and the energy loss at each reflection, it is possible to derive a formula for the average intensity at a distant point. This formula gives best agreement with experiment when the refraction is sufficiently strong to provide a fair number of cycles of bottom reflection.

Scattering of Sound—Reverberation

When a beam of sound is propagated through the sea, any obstruction which the beam encounters, or any departure from the ideal character of a homogeneous medium,

causes the diversion of a certain amount of sound into other directions. The term "scattered sound" is used to describe sound which has thus been removed from the main beam.

Sound which is scattered back in the direction of the transmitter is of special importance and gives rise to the "reverberation" heard in a sonar receiver. This reverberation appears in practice as a continuing background of sound associated with the received pulse echo. It usually covers a narrow frequency range around the mean pulse frequency and this serves to distinguish it from the general noise background always present in underwater sound work. Strong amplitude fluctuation with time is also a characteristic of reverberation, but superimposed on this is a long term decay. The importance of reverberation in echo-ranging is obvious since it may mask entirely a weak echo or occasionally mislead by simulating one. Experimental evidence shows that reverberation may arise from three distinct sources, *viz.*, the bottom, the surface, and the volume of the sea itself.

Bottom Reverberation

In shallow water the bottom is the main factor in producing reverberation. On the sonar range recorder the total reverberation intensity shows a fairly abrupt rise at a certain time interval after the pulse emission or at a certain range, as is commonly stated. Thereafter it decreases with range. This rise in reverberation intensity can be quite easily identified with the incidence of the horizontally directed sonar beam upon the sea bed. From the directionality of the emitted beam it can be deduced theoretically that this sudden rise in reverberation level should occur at a range between ten and twelve times the depth of the sea. In practice, however, by reason of the frequent occurrence of downward refraction this prediction is upset, and the observed ratio is, for the most part, between four and eight. It is interesting to point out that a subsidiary bank of reverberations at shorter ranges is often observed and can be attributed to the incidence upon the sea bed of radiation from the transmitter outside the primary beam (i.e., from the side lobes).

At ranges of such magnitude that we may expect bottom reverberation to occur, the other sources of reverberation are usually of lesser account, so that from the point of view of target detection it is important to know the intensity of the bottom reverberation and the way in which it varies with range and frequency. In this connection the things of significance in practice are the height of the initial peak of bottom reverberation and the law of variation of intensity with range.

Other things being equal, the height of the peak depends on the nature of the sea bed. It is usually highest over rock, less over sand and mud or over mud, and least over sand.

The peak increases in height as the grazing angle of incidence of the sound increases, either due to a downward tilting of the transmitter, or to a shelving upward of the sea bed in the direction of transmission, or again to a large downward refraction of the sound beam. An increase in the angle of grazing incidence of 30° may increase the reverberation intensity by the order of 10 db.

The intensity of bottom reverberation (including transmission attenuation) has been found in many cases to vary inversely as the fourth power of the range. There is no obvious explanation of this; in fact, an inverse third power of the range seems to be theoretically more reasonable. Whichever is correct, the implication is that (since the echo from a distant target will have a similar variation with range), an echo which is masked by the reverberation at the peak range will probably not be detectable beyond that range.

The scattering efficiencies of various types of sea bed show no pronounced variation with frequency. Observations have covered the frequency range from 10 to 80 kc and, though

the results differ among themselves to the extent of 6 db, this is considered less than experimental error. This more or less expected result is nevertheless important, as it indicates that, from the point of view of bottom reverberation only, no one frequency stands out as having particular advantages for echo detection.

Surface Reverberation

Bottom reverberation is eliminated if we transmit in sufficiently deep water. Here the reverberation is of a lower intensity. If, however, using a highly directional beam, we transmit downward instead of horizontally, we get even weaker reverberation. The implication is that a pronounced part of the reverberation encountered in horizontal transmission comes from the surface of the sea or from layers near the surface. This implication is supported by the finding that under conditions of strong downward refraction the reverberation intensity falls abruptly at a range at which one would calculate the beam to be refracted away from the surface layer. It is also supported by the observation that reverberation in horizontal transmission is much less when the sea is calm than when it is rough.

The origin of surface scattering is not yet understood. It might be caused by the irregular reflections from the waves on the surface of the sea when this surface is appreciably disturbed, or it might be caused by scattering matter or bubbles located in a surface layer. Irregular temperature distribution near the surface should also be considered.

The simple concept of a surface-scattering layer with uniform scattering coefficient leads to the result that the intensity of surface reverberation should diminish inversely as the cube of the range. Sometimes this has been found to be confirmed, but not often. The intensity normally falls off much more rapidly with range, and though various explanations can be suggested for this, the reason still remains obscure.

Further investigation has shown that the reverberation obtained in horizontal echo ranging in deep water can be attributed to surface contributions only at ranges up to about 1000 yards. The decrease of surface reverberation with increasing range is so rapid as a rule that at ranges above 1500 yards the only reverberation present appears to come from the volume of the sea. This conclusion is based on measurements of reverberation in relation to the state of the surface of the sea. The reverberation at short ranges is greatly increased when the sea is rough, as one would expect, but at ranges of the order of 1500 yards it is independent of wind and sea, which suggests that surface reverberation is at this range always swamped by reverberation from the volume of the sea.

Most of the foregoing conclusions have been derived from observations made at 24 kc. There appear to have been no comparative measurements made of surface reverberation over any extensive frequency range.

Volume Reverberation

When a highly directional transmitter is tilted downward in very deep water, so that the surface and bottom are precluded as sources of scattered sound, there is still a background of reverberation which one must attribute to scattering elements of some sort distributed throughout the sea. We are still ignorant of the cause of this scattering. Microvelocity fluctuations throughout the sea would be a source of some back-scattering, but evidence on the magnitude of the velocity fluctuations suggest that this source is not sufficiently powerful to explain the observed effects. The scattering may alternatively be attributed to foreign matter or small organisms dispersed throughout the sea. The scattering power of thermal currents should not be overlooked.

A survey of the scattering properties of the sea by means of a tilted transducer shows that the scattering power is not, in general, uniform

from point to point. If the distribution of scattering power were uniform, one would expect to find that the intensity of reverberation varies inversely as the square of the range, assuming that the transmission anomaly were negligible. In some cases this variation with range has been observed. But more often this simple relationship is invalid because the transmission anomaly is not negligible except at short ranges, and because the scattering activity is not uniformly distributed.

In particular, it is found that anomalous increases in scattering occur in a layer about 1000 feet deep. The form of this layer varies considerably, the distribution of scattering activity changing with time. Furthermore, the distributions of scattering as determined at frequencies of 10, 20, 40, and 80 kc rarely agree with one another satisfactorily. On the average, the sound scattered from this layer is about 10 db above the average value for volume reverberation. This layer appears to be of fairly general occurrence in ocean waters; thus in a cruise from San Diego to the Antarctic the effect was noticed all the way, though it was only intermittently present in the Antarctic itself. A remarkable feature of the layer is its diurnal variation in depth; the layer rises close to the surface of the sea at sundown, and sinks again to about 1000 feet at sunrise. It is presumed that the scattering in the layer arises from some sort of marine organism, but the type of organism has yet to be settled.

From the theoretical point of view the deep scattering layer is interesting since it appears adequate to account for the anomalously large intensities of sound in the shadow zones in cases of strong downward refraction. The intensity in the shadow is explained as being due to sound scattered forward and upward from the deep layer, which is itself directly irradiated by the sound refracted downward from a projector nearer the surface.

Measurements have been made of the intensity of volume reverberation in the scattering layer at frequencies of 10, 20, 40, and 80 kc. These measurements are not sufficiently accurate to enable one to say exactly how the volume scattering varies, but the results suggest a slight increase with frequency. It is possible to say, however, that the intensity does not increase as rapidly as the fourth power of the frequency as might be expected from the Rayleigh scattering law.

2. FUTURE RESEARCH

The Purposes and Value of Further Research

Opinions may differ as to the value of further research on transmission and scattering. On the one hand, it may be argued that underwater acoustics has been employed for naval purposes in one form or another since World War I and that over the last 10 or 20 years no really great fundamental advance has been made. Echo and listening ranges are now more or less what they were many years ago. From this it may be argued that substantial improvements in the range of detection are not to be looked for, but that the most we can do is to concentrate on technical improvements, getting the maximum amount of information in the shortest possible time within the limits of the present range of detection, and generally finding out precisely what the present limitations are.

On the other hand, it may be argued that a fundamental study of the acoustics of the sea may well reveal possibilities of greatly improved ranges of detection. [The discovery of the SOFAR channel, admitting of communication by sound over thousands of miles, is an indication that acoustics may have long-range applications. The long ranges at which SOFAR can operate do not necessarily imply any immediate prospects of long-range detection by listening, but they suggest, for example, that such detection is not impossible.]

Long-term research on transmission made

with a view to getting substantial improvements in the range of detection is somewhat of a gamble, but one which ought to be made because in no other field of physics is there any reasonable prospect of long-range detection of the submerged submarine.

But whether or not transmission studies are made to seek an increase in range of detection, there is much research that must be done even if that range always remains what it is now. We do not know enough about the *reliability* of sonar detection, which is often poor for reasons we do not always understand. Even if sonar equipment did not progress beyond its present form it would still be most important to have reliable information concerning the ranges of transmission to be expected at various times and conditions at any part of the world. There is as yet little direct information available on this point, other than that to be inferred from bathythermograph records. We still do not know how rapidly and how accurately we can transmit intelligence through the sea or obtain intelligence concerning a distant target.

These considerations have been borne in mind in suggesting the following scheme for future research. This includes some work reasonably certain to be of value, and other work aimed at extending our knowledge, with some chance of leading to worth-while improvements in sonar.

During World War II it was inevitable that research on sound transmission through water should be directed toward achieving results of more or less immediate practical value. Consequently, the research tended to be what may be called *operational* in character as distinct from the *academic* research which tries to broaden knowledge without an immediate practical end in mind. This is well illustrated by the rather narrow band of frequencies used in sonar transmission measurements, in the restriction to pulse sounds as contrasted to continuous wave radiation, in the measurement of reverberation largely by the echo method as contrasted to the more elaborate study of sound scattering by receivers placed outside the main beam, etc.

It seems almost axiomatic that further operational research and attempted refinement of sonar gear based on this research will lead to diminishing returns unless supplemented by vastly increased fundamental knowledge of all aspects of acoustic transmission in sea water. Much of this knowledge may not appear readily applicable at present, but all past experience shows that efficient technical advance in any field depends directly on the amount of fundamental information available. In this connection it is also worth stressing that further research on underwater transmission should not be hampered by restriction to those aspects which appear most closely connected with sonar ranging. We should rather take the attitude that we cannot really foresee all the possible uses of sound at sea which depend on transmission and that it is precisely such new uses which further academic research will suggest.

World-Wide Survey of Sonar Conditions

A vast amount of information on sonar conditions has already been obtained, but for the most part measurements of sound intensities were made off the coasts of New England and California. From these observations it was established that temperature gradients play a significant part in determining sonar conditions, as a result of which a "bathythermograph" was developed and was extensively used to obtain world-wide information of temperature gradients. It has then become the practice to infer acoustic conditions from the temperature records.

This procedure is convenient, but not very reliable. All the evidence shows that temperature gradients play a significant role, but it is not certain that field intensities and therefore echo or listening ranges can be deduced suffi-

ciently reliably from them to justify taking the thermal gradient as the sole determining factor in estimating such ranges. The measurement of the thermal gradient no doubt furnishes a first approximation to the desired result, and the world-wide survey of such gradients is justified thereby.

It is certainly true that there are other factors which affect the propagation of sound: salinity, scattering, surface and bottom reflections, microthermal structure, etc. It seems desirable in future assessments of world-wide sonar conditions to take these factors into account, and because we do not yet know how to do this properly, we should study sonar conditions by making actual acoustic measurements at each locality under consideration.

Such investigations might be made by studying the echoes from a target, using standard sonar gear, but in order to obtain information on listening ranges, studies should preferably be made of the transmission from a source to a distant receiver. In the past such investigations have been carried out using two ships, one for transmission and one for reception. It would clearly be desirable to eliminate the second ship if possible. This could be achieved by the use of a buoy in place of the second ship.

One possibility would be to employ a buoy from which is suspended at a certain depth a non-directional receiver. The ship approaches the buoy with its sonar projector trained on the receiver, transmitting signals at regular intervals. The buoy sends the received record back to the ship. The interval, measured on shipboard, between the outgoing pulse and the returned signal provides a measure of the range, provided knowledge of the average sound velocity in the water is available.

The scope of the proposed measurements of field intensity would depend on the facilities made available. It seems desirable to carry out these observations systematically and to cover really wide areas and the most widely different oceanographic conditions. The transmission runs themselves should be made with the listening hydrophone at various depths. It would be desirable to make observations at a wide range of frequencies covering, say, the interval 0.3 to 80 kc.

Economy might dictate the performance of the proposed measurements of field intensity as a part of a general oceanographic survey of various areas. In any case it is imperative that they be carried out by scientific personnel who are competent to analyze and interpret the data as they are obtained.

It would be most important to record simultaneously with the acoustic measurements all the physical and oceanographic factors on which the sound propagation could reasonably depend. These would include measurements of the vertical and horizontal velocity gradients, velocity fluctuations (microstructure), the state of the surface of the sea, thermal currents, the depth of the sea, as well as the nature of the sea bed.

This empirical approach to the problem of sound transmission would have a twofold value. In the first place, it would provide real evidence of the sonar conditions in the various localities studied, which would be of immediate value. Secondly, it would provide more extensive data in which to test out existing theories of sonar transmission.

At present we possess a theoretical framework which, though far from perfect, could be taken as a starting point and checked with any new set of data. With existing data we know that this theoretical structure gives a reasonably good account of things *on the average*, but is apt to be unreliable in certain circumstances. When the theory is tested by any new set of observations there may or may not be agreement in any one instance. At the present stage this is not a matter of great importance. But where there is a systematic discrepancy of a type hitherto not encountered it is clear that it points to a definite gap in the theory. Special

research effort should be made to generalize the theory so as to take account of the new effect.

It is unlikely that we already know all the things that can happen in sound propagation in the sea. As a case in point and as an illustration of the idea of the previous paragraph, some incidental observations were made in the Bahamas during the war on the low frequency propagation of sound. Most frequencies were propagated easily enough, but a certain frequency band was highly attenuated. There was not time to track down the cause of this, though a reasonable explanation was offered. This effect was unexpected and could be of importance. Another illustration of similar nature is presented by the highly absorbing blue clay in certain portions of the bottom of Chesapeake Bay. This produces a marked alteration in the shallow water transmission in its vicinity. There may be many other such effects of which we know nothing, simply because we have not made extensive enough experiments.

Model Scale Experiments

To supplement the somewhat empirical approach to underwater sound transmission put forward in the preceding section, it is further suggested that an attempt be made to develop a model technique for studying sonar problems.

A very serious difficulty in transmission research in the ocean is that the conditions of the experiment are not under control. It is rarely possible to find conditions in the sea which permit the unambiguous test of a theory of transmission. In practice various perturbing factors are present which mask to a greater or lesser degree the effect under investigation. As a result one usually finds only that a conclusion *tends* to be true, without being precisely true in all cases. It is, of course, an important practical aspect of our knowledge of transmission that we should know how the working of a particular hypothesis may be masked by other perturbing factors, but progress in understanding can best be made if we can isolate and confirm particular processes before we concern ourselves with these perturbing factors.

From this point of view the model technique appears very attractive, for we can carry out experiments in which all factors are under fairly good control. The ocean is such a complicated medium that it cannot be scaled exactly in the laboratory. However, a laboratory model can investigate sound transmission under conditions which, though controlled, are too complicated for the application of the established theory of compressional waves in a fluid. Such investigations can provide an insight into what actually happens in the sea. We may thus proceed on the working assumption that if, corresponding to any particular case of sound transmission in the sea, we set up a model with all frequencies increased in a ratio n and all linear dimensions scaled down by the same ratio n, transmission anomalies throughout the model will correspond to the original field. This assumption is not completely accurate, because the absorption coefficient of the sea is not correctly scaled, since it does not vary linearly with the frequency. but our knowledge of this absorption coefficient at high frequencies will permit the necessary correction. Even then one would hesitate to use the principle indiscriminately. The study of echoes from targets, for example, would be valid only if the natural vibrations of the target played no part in the process of reflection. The Rayleigh scattering of sound from small particles would also not be correctly scaled.

In spite of the above limitations there appear to be many problems for which the method would be practicable. Tentatively it is suggested that a scaling factor about 50 might be employed. Transmission of 20 kc in the sea would then correspond to 1 mc on the model. A horizontal range of 1000 yd. would appear as 20 yd. on the model. A transducer of di-

ameter 15 inches located at a depth of 15 ft. would be replaced by one of 0.3 inch in diameter at a depth of 3½ inches. Experiments of this scale would necessitate a tank of rather large size. Smaller tanks could be employed if the scale factor were increased, but it would be better to work with dimensions large enough to permit such factors as surface waves to be accurately simulated. Reflections from the sides of the tank would cause no confusion if short pulses were employed, and the received signals resolved on a time scale. Moreover, absorbing tank linings might be satisfactorily employed.

With such a model the following investigations could be carried out. We make sure to begin with that the salt water in the tank is quite stationary and isothermal, with no measurable velocity fluctuations.

(a) *Locating the transmitter* and receiver at positions where surface and bottom reflections cannot affect results, we first test the model by confirming that the intensity of the sound field follows the law (cf. the first section of Part 1):

$$I = I_0 e^{-aR}/R^2.$$

(b) In this connection it will also be useful to determine the beam patterns of a wide variety of transducers with respect to both intensity and phase. This is not strictly a transmission study but so closely connected therewith as to warrant investigation in a model experiment.

(c) Making sure that the water surface is perfectly calm we locate the transmitter and receiver at normal depths and explore the variation of field intensity with range to ascertain whether the Lloyd mirror effect is operative without any compromising assumption that the reflection coefficient may be other than unity as has hitherto been necessary.

This procedure is again a test of the model, and if the Lloyd mirror effect is not precisely found it would indicate that the model was not yet subject to sufficiently exact control. If the theoretically expected results are obtained in this simple case, we can safely go on to explore other situations too complicated for theory to handle. Thus we can introduce increasing degrees of wave disturbance on the surface of the tank and note how soon the Lloyd mirror interference pattern is broken down. This effect could easily be studied at lower frequencies, and it should then be possible to say whether in practice the deterioration of the interference patterns at higher frequencies is adequately accounted for by surface waves.

(d) It would then be useful to investigate the properties of thermal gradients. Beginning with a calm surface we endeavor to set up an accurately measured negative temperature gradient uniform over the whole of the tank. The sound intensity throughout the field including the shadow zone should then be measured. If, once more, the conditions in the model are sufficiently controlled, it should be possible to reproduce the results predicted by the wave theory of acoustic transmission for the sound intensities inside and outside the main beam. If the theoretical predictions of refraction theory are confirmed, it will be possible to investigate to what extent various perturbing factors can account for the discrepancies found in practice. The effect of surface waves could be studied in this connection. It should be possible to set up internal waves and study their effect on propagation. Finally, we could study the effect of a thermal microstructure. Such a microstructure might perhaps be set up by allowing a shower of cold water drops to play on the surface of the water. These cold drops would sink into the warmer water of the tank and produce small scale temperature variations. Larger scale fluctuations might be produced by suitable mechanical agitation of the water. Finally, we might stir the water up sufficiently to produce thermal fluctuations without any steady gra-

dient downwards. We could then study how this affects the propagation and how it influences the Lloyd mirror effect. Great care would be needed to avoid introducing any air bubbles by the mechanical agitation. Only a few resonant bubbles, so small as to be invisible, would completely mask the looked-for effects.

(e) Closely allied with the experiments in (d) would be studies of the refraction and diffraction produced by both stationary and moving obstacles in the path of the beam. Thus hollow cylinders and spheres of various sizes might be used to distort the beam. Dimensions both larger and smaller than the sound wavelength should be used. The diffraction and refraction effects due to rotating masses of water might also be investigated. Such experiments are actually underway or planned in the model tank at Brown University.

(f) Next it would be possible to study the influence of the sea bed on propagation. We could begin by using the highly reflecting metal bottom of the tank and study the propagation of low frequency sound. The reliability of the model would again be tested by comparing the results with the exact mathematical theory referred to in "shallow water transmission," Part 1. Tests could be carried out for various types of bottom reflecting surfaces, such as various depths of sand or mud. In each case the acoustic properties of the layer of sediment would admit of independent measurement. In the first instance such investigations could be carried out at the equivalent of sonic frequencies and with the surface of the sediment perfectly smooth and level, for which case the mathematical theory has been worked out. Later the work could be extended to higher frequencies and the effect of bottom roughness studied. Finally, the perturbing factors previously considered could be introduced one by one.

In these bottom investigations, we again build up a program starting from a mathematical model, and add perturbing influences until we approach conditions approximating those believed to exist in the sea. It should then be possible to see how far the original theory is applicable to the final structure and at what point it starts to break down.

It is realized that scaling difficulties will be encountered in the study of bottom reflection in a model tank but the independent measurement of the reflection properties of the bottom materials at high frequencies should provide the necessary correction. On the other hand, tests could be made with various sands with differing particle size and at various high frequencies, in the hope of finding sand which shows relatively little frequency effect arising from grain size.

Absorption of Sound in the Sea

In understanding the propagation of sound we must know how much sound is absorbed in its passage through the medium as distinct from that which is diverted from the main beam by refraction, scattering, or interference. Part of this absorption may be attributed to foreign matter present in the sea, such as micro-organisms. In this case it is desirable to know the absolute minimum of absorption exhibited by the pure homogeneous isothermal sea water as a function of salinity, temperature, and perhaps pressure.

As has been noted in the second section of Part 1, values of the absorption coefficient have been obtained for certain frequencies, though as yet our understanding of the processes involved has not progressed far. It is desirable to have reliable absorption values over a wide range of frequencies from about 100 cycles up to 10 megacycles for water under various conditions of salinity, temperature, and dissolved air content, and to ascertain the effect of fine suspended matter on these values. The carrying out of such a program is difficult at low frequencies in ordinary laboratory transmission measurements and difficult at all

frequencies at sea because of the various perturbing effects. The reverberation sphere method of Leonard and Liebermann appears to offer the best hope of success here. In this connection the attempt should be made to bridge the gap between the low frequency range up to 100 kc and the high frequency range beginning at 1 mc. It is particularly important to ascertain whether the variation of the absorption coefficient with the square of the frequency holds precisely in the lower frequency region or whether there exists a definite absorption or transmission band in the transition range.

Progress in the attainment of more accurate values of the absorption coefficient at low frequencies might be made by studying the propagation along a SOFAR channel, as has already been done in a preliminary way. However, in interpreting the results of SOFAR transmission in terms of intensities a careful analysis of the propagation along such a channel should be carried out by wave theory rather than by the approximate ray theory as has been done previously. A "wave guide" approach should be useful here; it has already been found helpful in studying transmission at low frequencies in the effective "channel" between the sea surface and a shallow bottom.

The problem of absorption should also be attacked from a theoretical standpoint. If a theoretically well founded formula could be established, agreeing with all experimental values so far measured, there would be fair grounds for extrapolating this formula into the lower frequency region. It must be confessed that the theory of sound absorption in liquids has offered considerable difficulty. Not only do the experimental values of the absorption coefficient exceed by a considerable amount the values calculated on the basis of classical viscosity theory, but the attempt to apply the *thermal* relaxation time theory, so successfully used in the explanation of absorption in gases, has failed completely for water. The suggestion has been made by Mandelstam, Leontovich, Tisza, Eckart, and others that structural relaxation may be involved. Dr. Eckart has recently worked out the general relaxation theory independently of any specific mechanism. Its application demands the introduction of two empirical constants, one of which is the relaxation time. L. H. Hall at Brown University has recently carried out a detailed calculation on the basis of the structural relaxation theory and has shown that, with the use of plausible hypotheses concerning the molecular structure of liquid water and its bulk viscosity, the theory can provide excellent agreement with experiment. It would appear to be in order to try to extend his calculations to lower frequencies and apply the method to salt solutions of various concentrations.

There is definite indication that the absorption coefficient of certain solutions (notably the acetates) over certain frequency regions in the megacycle range varies directly with the first power of the frequency rather than its square. There are indeed other frequency intervals where no power law will fit the data. It is of importance to ascertain ultimately whether this behavior is simulated for any frequency region in sea water. The empirical measurements at sea do indeed show a less rapid increase with frequency than the square in the region around 100 kc, but it must be remembered this includes the effects of scattering, reflections, refractions, etc.

The dependence of absorption on intensity should also be investigated. Experimental evidence so far available indicates an apparent increase with intensity. This may be due to cavitation produced by high intensity at the source, but it is also likely that the absorption mechanism for the non-linear phenomena associated with large amplitude sound will be rather different from that prevailing for the low amplitude radiation.

In the over-all absorption of sound in the sea many mechanisms doubtless contribute to

the final result. The role of scattering by aggregates of solid particles or air bubbles trapped in marine life should not be overlooked. Model experiments should be tried to separate out the net absorption due to these various causes.

The recent work of Cady on hydrodynamic flow should be examined further. He has shown that associated with high frequency radiation (i.e., of order of 1 megacycle) in water there is always a direct current action evidently associated with the momentum produced by the radiation pressure. This is produced not merely in the vicinity of the source but at every point traversed by the radiation. Though the effect is probably small in the 10- to 100-kc region, nevertheless it warrants further study for its bearing on sound transmission.

As a matter of fact, Eckart has recently shown that the hydrodynamic flow can be used to measure the bulk or dilatational viscosity of liquids. Preliminary experimental results of Liebermann indicate that for water the bulk viscosity is about twice the ordinary viscosity coefficient, quite in contradiction to the classical Stokes result in which the bulk viscosity is the negative of 2/3 the ordinary viscosity. This would bring the viscosity theory of dissipation of sound into better agreement with the observed absorption coefficients. This should be tested by application to other liquids.

Microstructure of the Sea

In a perfectly uniform medium a point source of sound will radiate waves which are always truly spherical, and at sufficiently large ranges become approximately plane over small areas. The intensity of the sound and the phase of the wave are then constant over an approximately plane surface whose normal is directed toward the source. In an imperfect medium which is liable to rapid fluctuations of velocity from point to point we cannot expect that this will remain so. We anticipate that the wave front will no longer be a plane (or more precisely a sphere) but a corrugated surface, and that the intensity will vary from point to point on this surface. Further, if an average plane is drawn through the corrugated surface, the normal to this plane need not accurately define the direction of the source.

These considerations point to fundamental limitations in the precision with which certain acoustic operations can be carred out. The use of an extremely directional hydrophone will result either in readings which fluctuate rapidly or in readings which do not reproduce the theoretical directionality of the hydrophone as the latter is trained round. As a result of such fluctuations there will be a limit to the precision with which even an apparent bearing indication of a point source of sound can be made, quite apart from any systematic error to which this apparent bearing may be liable. The theory of reflection of sound from smooth surfaces has been developed on the assumption that the incident sound field is either plane or spherical. Phase and intensity variations of the type we have been considering will modify correspondingly the phase relations of the incident sound over a reflecting surface, and will produce much the same effect as if a regular wave train were incident upon a roughened reflecting surface. The target strength of a large smooth surface will therefore depend somewhat on the microstructure of the medium. From other theoretical aspects it seems desirable to investigate these corrugated phase surfaces and their relation to the averaging properties of receivers used in underwater sound detection and to the various types of presentation of the received sound to the observer.

Another implication of these considerations is that a perfectly smooth sea bed will not now behave as a specular reflector. In particular, a horizontal sound beam will not necessarily be reflected forward without producing reverberation. Depending on the extent of the

microstructure the sea bottom will behave as a rough surface and produce reverberation at the source. For the same reason a perfectly smooth sea surface may not behave as a specular reflector of sound, and possibly this contributes to the poor manifestation of the Lloyd mirror effect at higher frequencies, even when the surface of the sea appears adequately calm.

Whether or not these particular speculations turn out to be of much practical significance, the study of small scale velocity fluctuations and their influence on sound propagation is a matter of importance on which little work has so far been done.

The problem may be approached experimentally in various ways: one possibility is to compare the intensities and phases of the sound received by a system of hydrophones located at equal distances from a common source of sound, and express the results statistically. It should be possible to express the probable difference in intensity and phase between any two points at the same range in terms of the separation of those points and of the range. At the same time an attempt should be made to deduce this information theoretically from measurements of the velocity microstructure.

Certain calculations already performed suggest that if phase fluctuations in the sound received at hydrophones equidistant from the source are due to relatively large masses of the medium performing rotational motions in the path of the radiation, this should lead to intensity fluctuations statistically correlated with the phase fluctuations. A similar situation should result if the fluctuation-producing entities are blobs of heated, though more or less stationary, masses of water. Further research is needed in this matter as it may well have a profound influence on the accuracy of the determination of bearings on a distant source.

The character of the phase surface at a very distant point will be influenced by reflections from the surface and bottom of the sea. The multitudinous and varying reflections from waves on the surface are bound to add to the complexity of the problem. It would therefore be desirable to carry out such measurements as have been suggested in the first instance under conditions where surface and bottom reflections are of no account. Later one could study the modifications introduced by surface and bottom reflections.

Development of a Sound Velocity Meter

In connection with the proposals for research at sea it was mentioned that it would be necessary to make simultaneous measurements of the sound velocity gradient. At present the widely used device for this purpose is the bathythermograph, which, of course, measures temperatures and not velocities. Its use for this purpose depends on the fact that the velocity of sound is largely determined by the temperature of the sea, and only to a lesser extent by salinity and pressure. This assumption, however, is not always justified, especially near river mouths where fresh water is being mixed with salt.

At present temperature measurements are supplemented, where it is thought necessary, by independent measurements of salinity. The influence of hydrostatic pressure is also estimated separately. It must be remembered, however, that the velocity is also influenced by any widespread distribution of air bubbles or even scattering particles in the sea. It is quite possible that bubbles are contained in marine life existing in the deep scattering layer (cf. second section of Part I). In this case velocity changes would occur through the layer which would be undetected by the present method of studying velocity gradients, although it is doubtful that these are so abundant as to decrease the sound velocity appreciably.

It seems very desirable to have available an instrument which can measure the sound ve-

locity directly. As a matter of fact, such a meter has already been devised employing a transmitter separated from a similar receiver by a short distance of the order of one foot. With a very high frequency transmission the phase difference between the received signal and the transmitted signal is appreciably affected by small changes in sound velocity, and these phase changes are measured and interpreted as velocity changes. The sensitivity of this instrument is proportional to both the frequency and the separation of the transmitter and receiver. The latter distance must be kept as small as possible, consistent with sensitivity, in order to achieve compactness. It would probably be better to keep the transmitter and receiver in the same vertical line so that the motion of the ship relative to the water will not influence the measurement of the velocity change. If the size of such an instrument could be kept small and if its operation were on the same level of difficulty as the present bathythermograph, this would facilitate the measurement of the change in sound velocity with time at any one place, as well as the velocity gradient in the case of slow temporal changes.

It is recommended that the sound velocity meter discussed here be made the subject of further research and development. Its sensitivity when designed for the measurement of gradients might not be adequate for the study of small fluctuations, but by working the same equipment at a higher frequency a proportionately increased sensitivity would result. It is admitted that to be of value its sensitivity should preferably be greater than that of the bathythermograph. It would be desirable to couple the output of such a velocity meter directly to a sonic ray plotter to speed the reduction of data.

Studies of the Sea Bed

Experiments which have so far been made in this field have been concerned with getting mean reflection coefficients for the sea bed as it actually occurs. It is recommended that more work of a precise nature be carried out, using a transmitter and receiver mounted some distance apart and at some height above the sea bed. The sea bed should be chosen as nearly flat as possible, and the other conditions of the experiment should be sufficiently under control so that completely reproducible records are obtained when the source emits a series of pulses. The amplitude and character of the reflected signal should be studied for various angles of the incident sound beam. From the results it should be possible to decide how the sea bed is behaving, i.e., whether as a simple impedance, a second fluid medium, or as a true solid medium in which transverse vibrations are being set up.

To answer these questions might require more accurate work than would be possible in the sea. Here it might be helpful again to use model scale experiments. Scaling difficulties and their solution have already been commented on at the end of the third section in this part of the report.

Further insight into the reflection characteristics of the sea bed might be obtained by studying its behavior as a transmitter of sound, i.e., velocity and attenuation. If the bottom functions as a fluid, the use of the latter values will lead by simple theory to reflection coefficients which can be compared with the experimentally determined ones. Also it would be interesting to see to what extent transverse vibrations can be set up in the sea bed. Work of this kind is actually going on in the Acoustics Laboratory of the Pennsylvania State College. It should be extended. The results so far indicate that the attenuation of sound by mud depends more or less directly on the presence of air bubbles. If these are driven out, the transmission increases considerably. This suggests that the same type of bottom may well show a difference in both its reflection and transmission characteristics at different depths.

Experimental work on this point should be initiated. Further laboratory tests on transmission through various types of materials actually encountered in sea bottoms should also be undertaken. Theoretical studies of the reason for the higher absorption in certain clays (e.g., the Chesapeake Bay variety) are also recommended.

Low frequency sound is certainly capable of being transmitted along the sea bed. When an underwater explosion is picked up on a distant hydrophone the first sound wave to arrive can often be shown to have pursued a path lying mainly in the sea bed. The velocity of propagation there is higher than that in the water, and it seems likely that the deeper layers of the sea bed will have still higher velocities. The top layers should then function as a sound channel, for the positive velocity gradient in the sea bed would keep the sound bent upwards, and the discontinuity between the water and the bed would tend to prevent the escape of sound into the sea. The sound would then be canalized near the surface of the sea bed, and long-range propagation at sufficiently low frequencies should then be possible.

Improvements in Dome Design of Transducers

In shipborne sonar applications an important problem is the passages of sound from the transducer through the protective dome to the sea outside.

A satisfactory dome must be sufficiently streamlined to produce minimum noise in its passage through the water. It must be sufficiently strong to withstand the considerable water pressures at the speed at which it is required to operate. Lastly, it must produce minimum attenuation of the outgoing or incoming sound and, even more important, must produce minimum distortion of the transducer beam pattern.

These requirements are conflicting; sound transparency, for example, can usually be improved at the expense of mechanical strength. In the past domes have been constructed of thin sheets of steel mounted on a strong steel framework. In this construction the strength is provided mainly by the framework. At present, there is a need for domes which will preserve the beam pattern for all orientations of the transducer in both the horizontal and vertical planes. This has led to the design of a dome moulded from rubber, and streamlined in both horizontal and vertical planes. This dome has sufficient thickness of rubber to provide a major part of its strength. The moulding is built upon a framework of relatively thin steel wire.

This design is attractive, and its success will depend largely on finding a suitable rubber which provides adequate strength combined with the necessary acoustic transparency.

Research on Reverberation

In shallow water the background reverberation is the factor which limits detection by echo-ranging methods. It is, therefore, important to know to what extent reverberation might be reduced under various conditions, e.g., (a) by shortening the transmission length, (b) by a suitable choice of frequency, or modulation of frequencies, and (c) by increasing the beam concentration of the transducer.

Further experiments along this line should be carried out. We know that the reverberation is approximately proportional to the transmission length, but this has only been verified over the comparatively limited range of 10 - 80 millisec. We ought to know if the rule applies down to transmissions of (say) 100 microseconds. Presumably a decided decrease in transmission length will produce a sharp decrease in the reverberation. However, it must be remembered that this is inevitably associated with an increase in the frequency spread of the transmitted pulse, which would work against the use of the Doppler effect to measure motion of the target. Moreover, the ultra

short pulse has the disadvantage that it may be confused with random noise spikes which can readily be distinguished from longer pulses. On the other hand, the use of short pulses might yield scientific results of great value concerning the number of scattering elements per unit volume, since the irradiated region would then be reduced in size to the point where the Poisson distribution might apply. It is recognized that the production of ultra short pulses will demand changes in transducer and auxiliary circuit to diminish their relaxation times.

Further work is desirable on the variation of reverberation with frequency. Previous results have tended to be indecisive, and probably the accuracy of the measurements and calibration could be improved, particularly with surface reverberation, which does not seem to have been much studied except at 24 kc.

There is no experimental information about the reduction of reverberation by an increased beam concentration. Theory points to a simple formula relating the two, but here, as in other aspects of reverberation theory, simple results have been obtained on the assumption that multiple scattering of sound does not count. Experiments should therefore be performed which are either aimed at a direct verification of these theoretical predictions, or are concerned with a closer analysis of multiple scattering.

Multiple scattering would be of no consequence if we knew that sound was always uniformly scattered in all directions, for then the relative smallness of reverberation in relation to the direct transmission would justify us in concluding that sound that has been twice scattered is always of a much smaller magnitude than sound scattered only once. The question, therefore, reduces to one concerning the way in which sound is scattered in directions other than back towards the transmitter. For this reason investigations should be made of the sound scattered in various directions by (a) the volume of the sea, (b) the surface of the sea, and (c) the bottom of the sea.

Bottom Reverberation

Research on bottom scattering might be helped by the use of the model technique suggested in the third section. Here it would be feasible to make careful observations of the nature and contour of actual sea beds, and then to reproduce similar contours in the model tank, using a sediment bed. It would be instructive to compare the actual magnitude of the tank reverberation with that obtained at full scale, making allowance for any differences in the reflection characteristics of the two beds. It would be possible with the model to study accurately the influence of grazing angle of incidence on the reverberation level, especially for very small grazing angles. We could also investigate how the intensity varies with the degree of roughness of the sea bed and get some indication of the scattering in various directions.

Surface Reverberation

The model technique could also be used to study surface reverberation. Here we have the advantage that the reflection coefficient of the surface of the sea is the same at model scale as at full scale, though the difficulty in simulating accurately the nature of the surface disturbances would be greater. In such experiments we could measure reverberation which is due entirely to the perturbed state of the water surface, and not due to the presence of scattering centers beneath the surface. It should, therefore, be possible to get an idea of the extent to which surface waves alone are directly responsible for reverberation.

The reverberation from scattering centers located in the surface layers of the sea could be studied at sea by employing an echo-ranging transducer in an inverted position be-

neath the surface, much as has already been done in wave measurements. By using a sufficiently directional transducer at a sufficiently small distance beneath the surface, it should be possible to measure the scattering from any centers quite close to the surface before the first strong surface echo comes in. In this way, just as in the vertical investigations of the deep scattering layer, one could give a value to the scattering power of such a layer quite apart from any scattering power of the waves themselves. This should be done over a wide frequency range.

The anomalously high rate of decay of surface reverberation could be studied by taking measurements from a submarine fitted with a tiltable echo ranging transmitter. Most of the explanations of the rapid decay of surface reverberation are based on the increasingly small angles of grazing incidence with which the sound impinges on the surface at large ranges. If, however, surface reverberation were measured from a submarine at various depths, with its transducer set horizontal, then reverberations, for which the conditions of incidence were identical, could be compared at differing ranges. We should then expect the inverse cube law of intensity variation to be more accurately applicable. Additional information on the reasons for the more rapid decay in practice could then be obtained by tilting the transducer upwards at various angles and at various depths, and finding how the scattering effect of the surface depends on the angle of incidence.

In this and all reverberation studies at sea it should be remembered that a measurement of reverberation depends upon the transmission loss which the sound experiences in traveling to and from the various scattering centers as well as upon the intrinsic scattering properties of these centers. Exact information concerning the former is essential if we are to use our measurements to give us exact information about the scattering which is the fundamental cause of the reverberation. The value of many earlier reverberation measurements has been impaired because it has been necessary to speculate on the precise value of the transmission loss operative at the time of the measurements. It is, therefore, desirable when making reverberation measurements, except perhaps at very short ranges, to make corresponding measurements of the transmission characteristics of the sea. Attempts to do this at San Diego during the war were not very successful, largely because of the variability of sound transmission in the sea. Further work on this is nevertheless highly recommended.

Supplementary Suggestions on Reverberation

The previous sections suggest further direct research on specific types of reverberation both at sea and in model tanks. It will be wise not to overlook more intensive study of the nature of the scattering centers responsible for reverberation. Model tank experiments should attempt to distinguish between the scattering power of surface distortions on the one hand and bubbles on the other.

The fact that the scattering involved in volume reverberation does not vary with the frequency in the manner demanded by the Rayleigh fourth power law but that rather the variation is generally very slight suggests that the volume scattering centers have dimensions of the order of the wave-length or larger. The possible connection between volume reverberation and microstructure of the sea is thus not entirely ruled out. This is another field for model tank investigation.

It is now generally believed that the deep scattering layer referred to in the eleventh section of Part 1 is due to organic material, possibly living animals containing air bubbles. Experiments might be undertaken in the model tank to see whether it is possible to maintain a layer of bubble-like scattering elements at a preassigned depth and if so to test their scat-

tering ability. It is also desirable to conduct biological and oceanographic studies of the layer at sea to try to find out just what is really down there. The attempt should be made to correlate the intensity of the sound appearing inside the shadow zones predicted by ray acoustics with the appearance and location of the deep scattering layer.

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CHAPTER

5

Fluctuation of Sound in the Sea

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1. INTRODUCTION

General Discussion

If sound of constant intensity and frequency is transmitted through the sea from one ship and received on another at some fixed distance, the intensity of the signal received from one second to the next will not be constant; it fluctuates, often by a factor of ten. Indeed, the presence of fluctuation is perhaps the most constant characteristic of sound in the sea! This fluctuation is very apparent when the reception is by ear; the loudness of the sound increases and decreases in an easily perceptible but very irregular manner. The same effect is noticed when sound is transmitted through the open air; it is commonly said that the wind "blows the sound away." A similar effect ("fading") is also found in the transmission of radio waves.

In air the cause of this fluctuation is the changing condition of the transmitting medium: the sound or radio wave passes through regions which are inhomogeneous and which are in relative motion, and this in turn causes changes in the transmission. Likewise, in the sea, the condition of the water is constantly changing and this causes fluctuation in the transmission. It will appear, however, that a large part of the fluctuation is caused by the changing condition of the sea surface, which thus affects the transmission via surface reflections. A further cause of fluctuation in the sea is the relative motion of the ships from which the source and receiver are usually suspended. Thus the source and receiver may be in relative motion with respect to each other, to the water, and to the surface and bottom, all of which change the path of the sound traveling from source to receiver. Both of these factors, the motion of the surface and the motion of the source and receiver, are usually absent in the transmission of sound and radio waves in the air, and in this sense the fluctuation of sound in the sea may be expected to be a more complex phenomenon.

Importance of Fluctuation

Fluctuation of transmitted sound in the sea is of interest in three fields: (1) scientific research, (2) operation of sound gear, and (3) design of equipment.

Scientific Research. Fluctuation is important in scientific studies for several reasons. First, since fluctuation is random in nature it necessitates a statistical approach to underwater sound problems. Thus, in taking data, numerous and repeated measurements are

necessary in order to obtain reliable curves of the average transmission under given conditions. From 5 to 10 signals equally spaced on a 15- to 30-sec. interval were used at each range in determining the average transmission curve for the sound field runs made at San Diego. Again, fluctuation influences to a considerable extent the analysis and interpretation of transmission data.

Second, fluctuation may serve as an indication of the mechanisms operating in the transmission of sound. Knowledge of these mechanisms, e.g., scattering and surface and bottom reflection, is of great value in the understanding of both reverberation and transmission and in the effective use of transmission data, for example, in the prediction of maximum listening and echo ranges.

Third, the predictions can only be statistical in nature. This is the converse of the measurement problem mentioned above.

Operation of Sound Gear. Fluctuation plays an important role in the detection and recognition of echoes or signals. For many practical purposes fluctuation can be ignored and its effects eliminated by averaging 5 to 10 successive signals. This is possible, for example, in most echo-sounding operations, where there is time to consider several echoes before arriving at a conclusion. In search operations, however, where the area being searched is swept by the sound beam, only one or two echoes may be received from each direction. When fluctuations make these echoes especially weak, a target may escape detection altogether, even though it is within the average sound range. On the other hand, if the target is outside the average sound range, an abnormally strong echo may lead to its detection. These considerations are of vital importance in assessing the probability that a useful echo will be obtained from any one ping. Finally, fluctuation is an important factor in determining the detectability of echoes of ship noises, since in general both signal and background are subject to fluctuation.

Design of Equipment. In the design of equipment knowledge of fluctuation may be of importance in various ways. For example, knowledge of the time coherence of fluctuation may allow one to anticipate the amplitude of a given signal or reverberation, by using the preceding signals or reverberations. Again, in designing equipment which operates on a threshold level, it may be important to know the variability and structure of the received signals.

Scope of this Digest

This digest has three aims with regard to the fluctuation of sound in the sea:

(1) To discuss the scientific problems presented by fluctuation.

(2) To summarize present knowledge of fluctuation.

(3) To suggest the lines along which further research is likely to be most fruitful.

Attention will be restricted to the fluctuation of transmitted signals only; the fluctuation of reverberation and echoes will not be treated. The general theory of reverberation is given in reference 1, as well as some data regarding its fluctuation. So far as echoes are concerned, it is well established that their fluctuation cannot be calculated from the fluctuation of transmission alone; a detailed knowledge of the structure of the target is also necessary. A discussion of these matters would take us too far from the subject of primary interest: namely, the fundamental oceanic mechanisms that cause fluctuation.

2. FACTORS AND MECHANISMS INVOLVED IN FLUCTUATION

Before considering the experimental data and the conclusions to be drawn therefrom (Parts 3 and 4), the general picture of transmission and fluctuation under certain idealized conditions will first be considered briefly. This section is therefore a purely descriptive and

theoretical discussion. Such a discussion will serve two purposes. First, it will provide a background against which the various mechanisms involved in fluctuation can be exhibited; second, it will clarify the significance and interrelation of the various items of experimental evidence. After a qualitative description we shall discuss factors and mechanisms. By "factors" we shall mean independent variables such as frequency, hydrophone depth, thermal structure, etc. By "mechanisms" we mean such things as scattering, surface reflection, etc., which provide possible explanations of fluctuation. The two categories, of course, overlap and cannot be separated, even in theory. This dual viewpoint is necessary because the experimental data give a direct measure of the effect of the various factors on fluctuation, while the theories deal with combinations of the factors in certain mechanisms. Since the experimental results have not yet been fitted into any general theory, it seems wise to present the available facts independently of the various possible mechanisms. An attempt will be made later to relate the facts to the theories and reach some tentative conclusions.

Qualitative Description

Figure 1 shows schematically three idealized situations for sound transmission measurements. In Fig. 1A the sea is represented as a semi-infinite homogeneous isotropic medium, bounded by a flat "mirror" surface. The projector P and hydrophone H are supported rigidly in space and are non-directional. These circumstances are ideally approached in the limit of low frequencies, deep water, smooth surface, negligible thermal gradients, and steady ships. The intensity in space is given by the familiar image interference (or Lloyd Mirror) pattern resulting from interference between the direct and surface-reflected sound. The intensity received by the hydrophone is constant and there is no fluctuation.

In Fig. 1B the situation is complicated by two factors: (1) the surface is rough and is in motion; (2) the projector and hydrophone are directional. These conditions are approached in deep water at intermediate frequencies and moderate ranges (say 10 kc at 300 yards), there being weak refraction, low sea state, and no swell. Here there may be one, several, or many surface reflected rays, depending on the scale of the surface roughness, the signal wavelength, and the degree of directionality of the transducers. These surface reflected rays will interfere with the direct signal and produce fluctuation. The effects of the directionality of projector and hydrophone will be negligible for the rays emitted and received in the central part of the main lobe. When the projector and hydrophone are at depths comparable to the range, however, directionality will discriminate against the surface-reflected sound. Thus only the direct signal (shortest path) will be received, and it should be steady regardless of the surface conditions.

Finally, in Fig. 1C the remaining complications are added to complete the picture of actual transmission at high frequencies. These consist of (1) ship-mounted transducers; (2) the sea bottom; (3) thermal and salinity gradients; and (4) inhomogeneities in the medium. The effects of these factors are as follows: First, the projector and hydrophone are no longer mounted rigidly in space but are supported by ships which pitch and roll and drift, even when they are "dead in the water." With highly directional transducers it is clear that a large roll, for example, will introduce changes in the intensity of the signal recorded on the receiving ship. Again, if there is a "fine-grained" spatial interference pattern (say, 1 foot between maxima and minima), then even small relative motions of the projector and hydrophone will give rise to intensity fluctuations from second to second.

In the second place, the presence of the bottom results in reflections which will, in general, interfere with both the direct and surface reflected sound and produce complex interference patterns. Since the bottom is

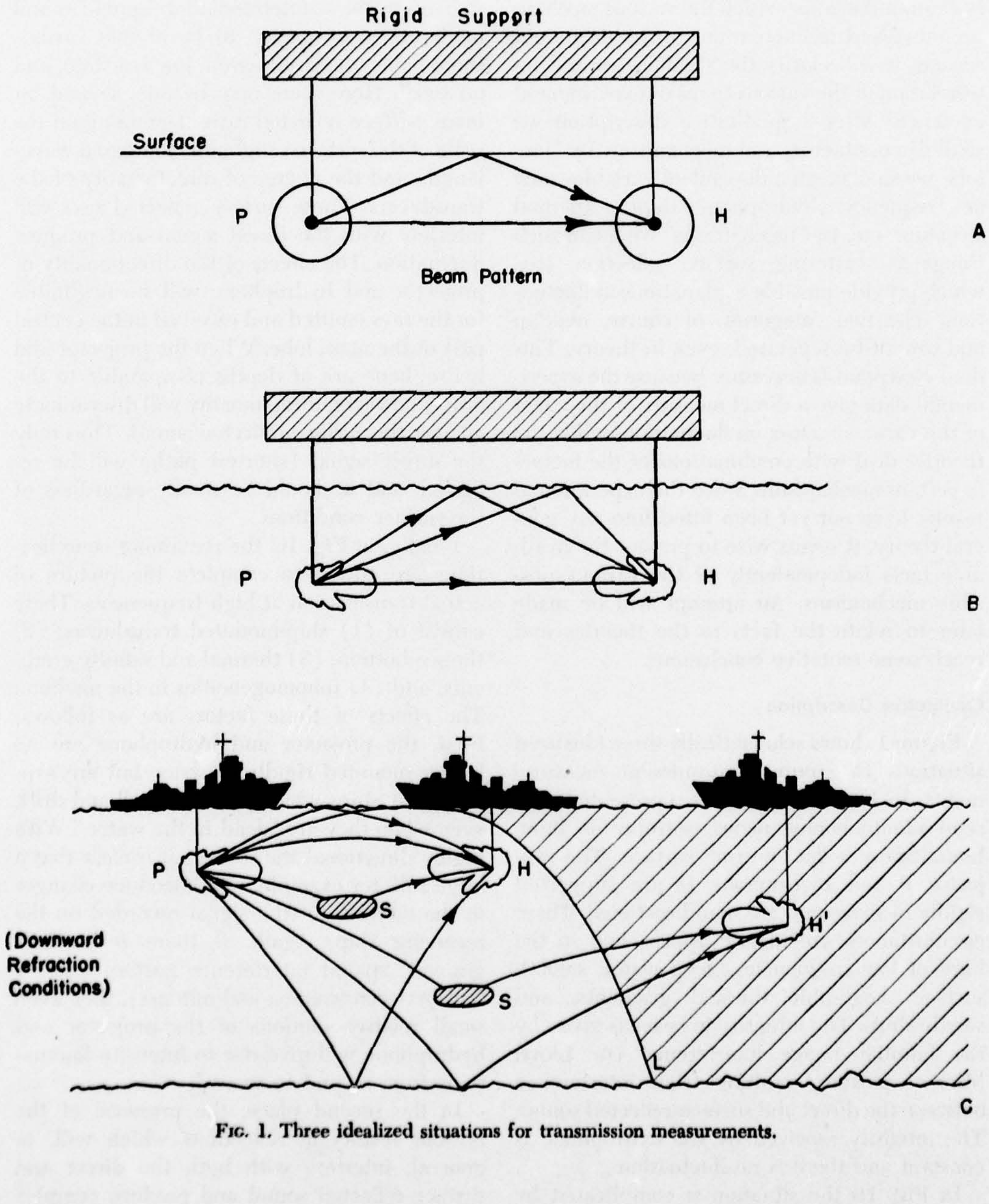

Fig. 1. Three idealized situations for transmission measurements.

rough and projector and hydrophone are in motion relative to the bottom, the phase and intensity of the bottom-reflected sound will not be constant but will vary, even though the range between the sending and receiving ship is constant. It should be noted that the signal duration must be long for these effects to occur in deep water, since there is a large time lag between the direct- and bottom-reflected sound. By using short pulses, the direct- and bottom-reflected signals can be separated and prevented from interfering. In shallow water it is only possible to separate the direct, bottom, and surface signals by using extremely short pulses, which introduce technical difficulties.

Third, there are thermal and salinity gradients which change the velocity of sound in the water and refract the sound rays, thus changing their divergence and altering the intensity of the sound field. Figure 1C shows the familiar case of downward refraction. This results in a shadow zone, bounded by a limiting ray (L) which grazes the surface; ray theory predicts that no direct sound can penetrate this region. Deep in the shadow zone, therefore, the sound received by a hydrophone (H′) must be transmitted via bottom reflections or via scatterers (S) in the water. Near the limiting ray diffraction will allow some sound to penetrate the shadow. Moreover, because of internal motions in the sea, the limiting ray is not stationary but is constantly moving irregularly, so that the hydrophone may be in the direct field for one ping and in the shadow zone for the next.

Fourth, there are inhomogeneities in the water, such as suspended matter, bubbles, internal waves, or thermal structure. These will cause the sound field intensity to vary from point to point and from time to time because of scattering and absorption, thus providing another source of fluctuation.

Summary of Factors and Mechanisms

In this section we shall summarize the various factors involved in fluctuation. Since little is known about the causes of fluctuation, it is intended that the list should be quite complete, even though certain of the factors can be eliminated in practical cases. Such a list will be of help in understanding the complexity of the problem; it should also serve as a reminder of the incompleteness of the various theories in which some of the factors (e.g., relative motion of the ships) are tacitly omitted.

TABLE I. Summary of factors influencing fluctuation.

1. Signal
   - Frequency
   - Duration (length of wave train)
   - Interval between successive signals
2. Projector-Hydrophone
   - Range
   - Depth
   - Directivity
   - Orientation
   - Relative motion
   - Power output of projector
   - Sensitivity of hydrophone and circuits
3. Water
   - Thermal and salinity gradients
   - Thermal inhomogeneities
   - Thermal layers and internal waves
   - Volume scatterers
4. Surface
   - Form and scale of irregularities (sea and swell)
   - Motion
   - Aerated layers (white caps)
5. Bottom
   - Depth
   - Type of material
   - Form of bottom surface
6. Experimental
   - Procedure during experiment
   - Motion of ships
   - Recording and processing of data

The following mechanisms were mentioned

in the preceding section or have been discussed in the literature as possible causes of *fluctuation*:

TABLE II. Summary of possible mechanisms causing fluctuation.

1. Roll and Pitch of Sending Ship
2. Relative Motion of Projector and Hydrophone
3. Interference between Direct and Surface-Reflected Sound
4. Interference between Rays Bent by Thermal, Micro or Macro Structure
5. Focussing and Defocussing by Thermal Inhomogeneities (lens action)
6. Reflection and Scattering from Inhomogeneities in the Sea
7. Interference between Direct, Surface-Reflected and Bottom-Reflected Sound

These mechanisms are not all independent; they are listed separately either because they have been studied individually or because the experimental data suggest their isolation. In the sea it is probable that all are present to some degree at all times.

The Problem of Fluctuation

We may now phrase the more important aspects of the problem of the fluctuation of underwater sound signals by asking five very general questions:

(1) What is the
- (a) Average magnitude of the fluctuation?
- (b) Average rate of fluctuation, i.e., the rate of change, in time and space, of the signal amplitudes?
- (c) Statistical distribution of signal amplitudes as a function of the factors listed in Table I?

(2) What mechanisms contribute to the fluctuation and what is their relative importance, particularly as a function of frequency and range?

(3) To what extent can the fluctuation be predicted?

(4) To what extent can the amplitude of an individual signal in such a sequence be predicted?

(5) What is the effect of fluctuation on the detection and recognition of underwater sound signals and echoes?

In the following sections (Parts 3 and 4) we shall summarize the various experimental results now available and shall draw some general conclusions which provide tentative answers to the above questions. In Part 5 we shall return to these questions and attempt to indicate the additional research necessary to answer them.

3. EXPERIMENTAL RESULTS

In this section we shall summarize the available experimental data regarding the fluctuation of sound in the sea. This information is not adequate for even a semiquantitative theory of fluctuation. It does, however, shed light on the relative importance of various mechanisms involved and leads to some tentative but useful conclusions.

While much of the experimental work was done by UCDWR during sound field and reverberation experiments, significant experiments were also made by the Naval Research Laboratory, the Naval Ordnance Laboratory, the Woods Hole Oceanographic Institution, and the Navy Electronics Laboratory (formerly the U. S. Navy Radio and Sound Laboratory). Since most of the data were taken in deep water at 24 kc, the results will be understood to refer to transmission at this frequency in the absence of bottom reflections, unless otherwise noted.

Dependence of Fluctuation on Range and Frequency

Typical Records at 24 kc

Some typical oscillograms* of 24-kc signals received during ship-to-ship transmission at various ranges are reproduced in Figs. 2, 3, and 4. Each strip of 35-mm paper carries three galvanometer traces (see Fig. 3), the top is the signal received via radio; the center is the signal received through the water, while the bottom is the 60-c.p.s. timing trace, with 10-c.p.s. pips superposed. These are records of short pings (of 100 milliseconds in duration) transmitted successively a half-second apart. Once each minute a long signal (10 seconds) was transmitted (Fig. 4). Comparison of the difference in travel time of the sound and radio signals gives the range between the transmitting and receiving ships, the former being under way.

The signal emitted by the projector is a pulse with rectangular envelope. Pulses picked up on a hydrophone suspended overside from the transmitting ship are illustrated in Fig. 2. The amplitudes of the successive pings do not vary appreciably.

The measurements of Figs. 3 and 4 were made in 600-fathom water off the California coast. The hydrophone depth was 75 feet, the projector was mounted on the sending ship at a depth of 16 feet, approaching at 12 knots. In Fig. 5A, the intensity level is shown on a logarithmic range scale. Each point represents an average of 5 amplitudes at ranges chosen to reveal the general trend of the curve. The upper solid curve represents the level of the direct signal while the lower dashed curves represent the level of the reverberation following the direct signal and of the bottom reflection, respectively. The transmission curve is plotted in the anomaly form[1] in Fig. 5C.

* Figures 3, 4, 5, and 17 all refer to data taken during one run (Reel 6; July 6, 1943).

[1] NRDC, *Summary Technical Report*, Vol. 6-VII and 6-VIII.

There was strong downward refraction during this run, as shown by the ray diagram of Fig. 5B. The limiting ray which grazes the surface and limits the direct sound field indicates that the range of the shadow zone at the hydrophone depth is about 700 yards. The intensity drop at this range shows rough agreement with the simple ray picture but disagrees completely at greater ranges, where a low intensity is observed instead of the silence predicted by the ray theory.

Transmission of 24-kc Pings

These general characteristics of the average sound field are closely connected with the fluctuation of the signals shown in Figs. 3 and 4, to which we now turn. When sharp downward refraction is present, the most striking feature of the records at ranges greater than 100 yards are the progressive changes in the shape of the received pulse, shown diagrammatically in Fig. 6, and these will be discussed before the quantitative features of fluctuation are presented. At short ranges (Figs. 3 and 4) the envelope of the signals is "smooth," i.e., the amplitude shows little variation during time intervals of the order of 10 milliseconds. Over greater intervals, i.e., one signal interval or greater, the magnitude of the fluctuation of pulse amplitude is surprisingly large even at short ranges; in Fig. 3A, the last signal but one is almost imperceptible and the maximum amplitude for this range is more than 20 db higher.

As the range increases (say, to 800 yards which is within the acoustical shadow) the signals become rapidly weaker, but the sharp beginning and end of the pulse, characteristic of short ranges, is retained. However, the main pulse is now followed by a "tail" of lower amplitude and irregular envelope. This tail has the character of reverberation (scattered sound); it is probably present at shorter ranges as well, but does not appear on the record because of its relative weakness compared to

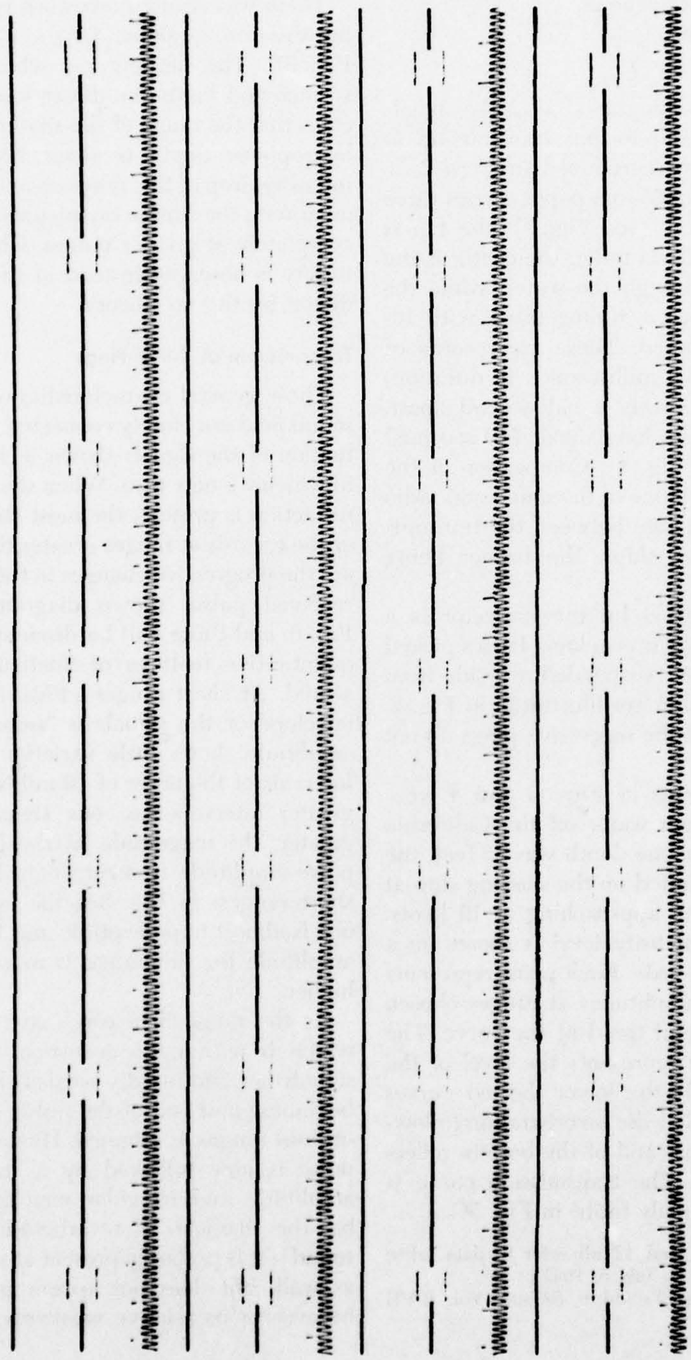

FIG. 2. Supersonic signals, range = 13 feet.

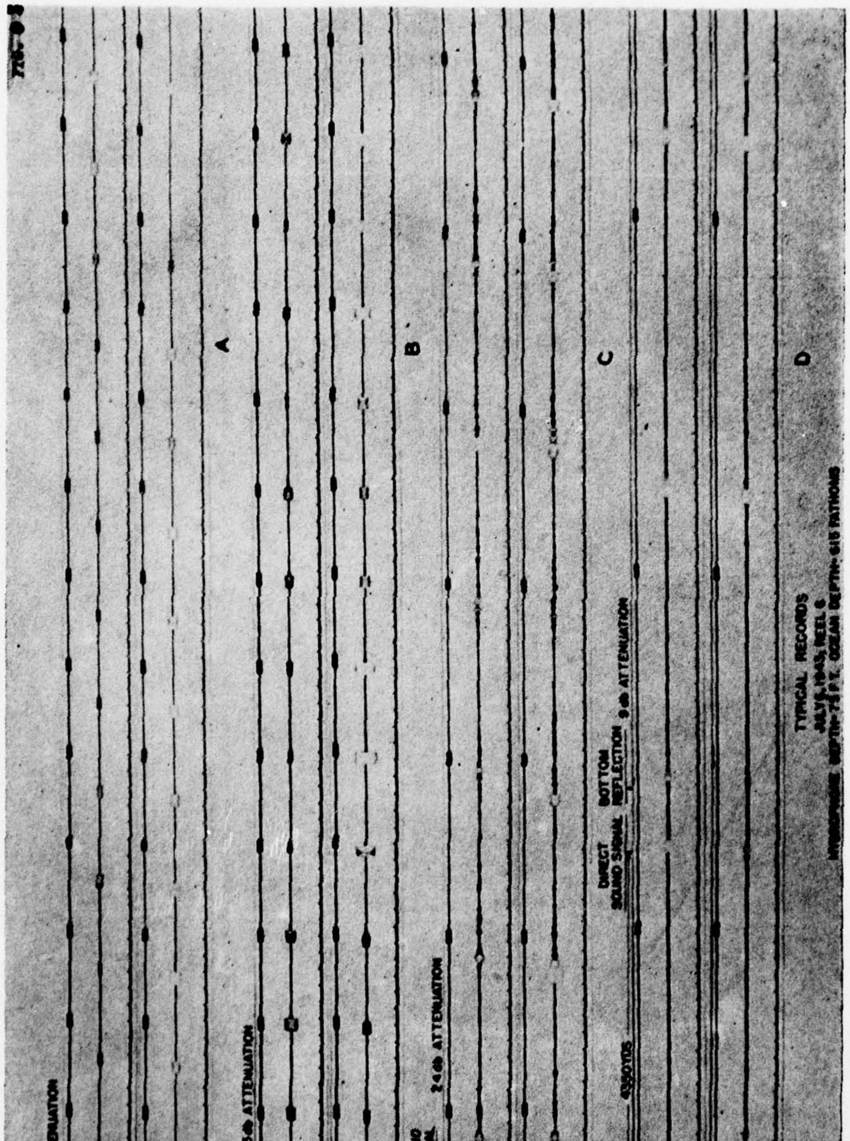

FIG. 3. Supersonic signals, range = 450 to 4500 yards.

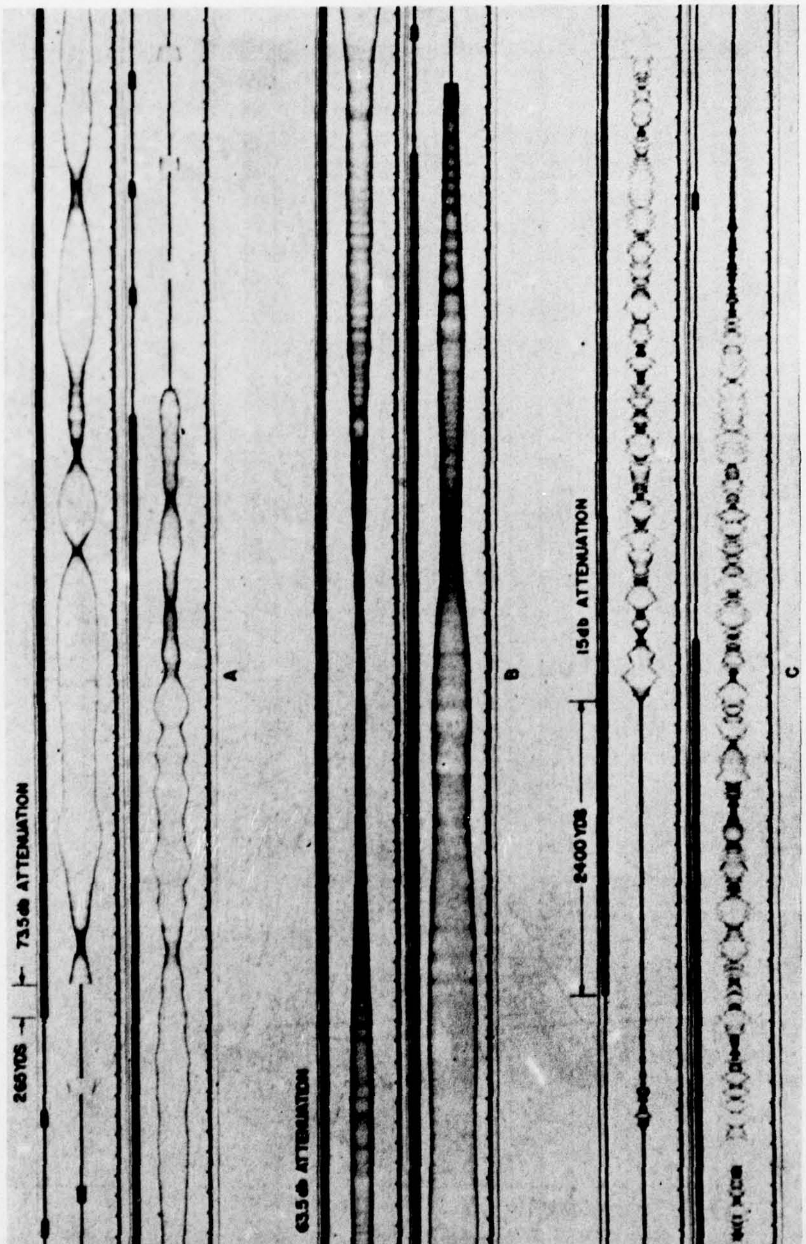

FIG. 4. Long supersonic signals, range 250 to 2500 yards.

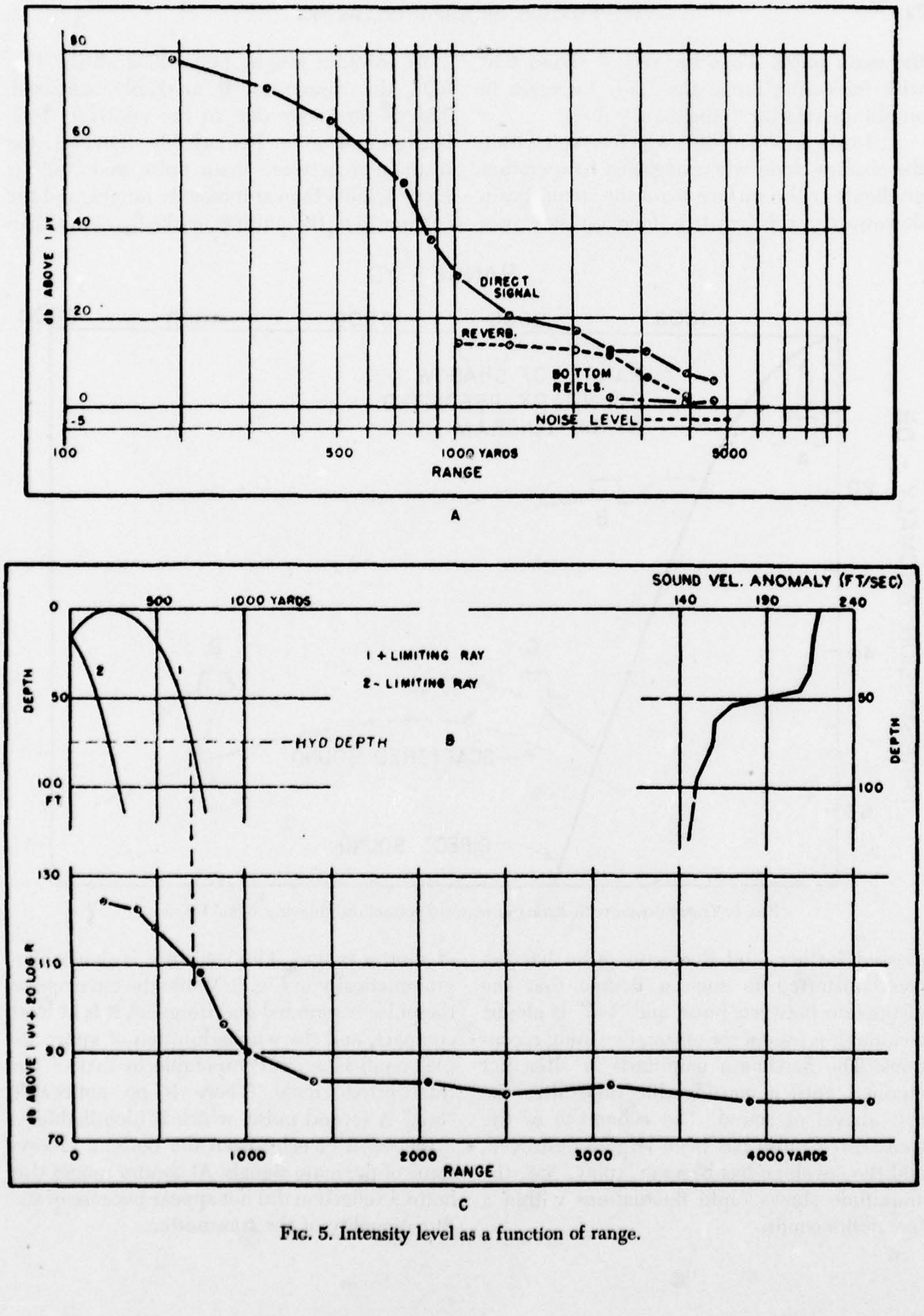

FIG. 5. Intensity level as a function of range.

the main pulse. Thus the record shows that with increasing range the "tail" increases in amplitude relative to the main pulse.

At 1340 yards (Fig. 3C), which is well within the shadow zone when negative temperature gradients at the surface bend the sound beam downwards, this relative increase has progressed further, and the main pulse has become distorted to such a degree that the distinction between pulse and "tail" is almost meaningless except for unusually strong receptions. The maximum amplitude is often not attained until a considerable time after the first arrival of sound. The coherence of the transmitted pulse has been largely destroyed, and the envelope has become "spiny," i.e., the amplitude shows rapid fluctuations within a few milliseconds.

At extreme ranges (say, 4300 yards, Fig. 3D), the "spinyness" is markedly increased. This is obviously due to the relatively high background noise. Remarkably, however, the *distinction between main pulse and "tail"* is more definite than at moderate ranges, and the coherence of the pulse is markedly better than at shorter ranges. This structure is shown diagrammatically in Fig. 6. While the envelope of the pulse is rounded and irregular, it is at least compact, and the whole duration of appreciable sound is again comparable to that of the transmitted signal. There *is no noticeable* "tail." A second pulse, which is identifiable as a reflection or echo from the bottom, follows some of the main signals. At shorter ranges this bottom reflection did not appear because of the directionality of the transmitter.

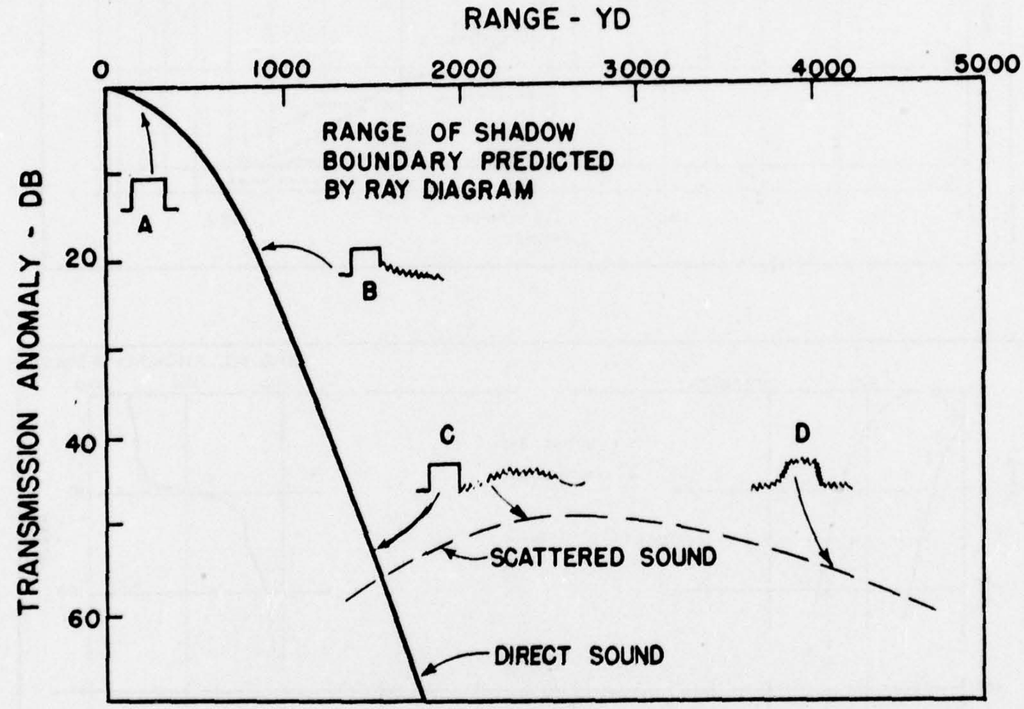

FIG. 6. Transmission with strong downward refraction, showing signal forms.

In isothermal water the direct sound reaches a hydrophone near the surface at all ranges. In this case the signal remains coherent at all ranges, and the rate of fluctuation decreases rather than increases; this effect is discussed subsequently.

Long Signals at 24 kc

Other characteristics of the fluctuation are shown by the long 10-second signals which are transmitted at one-minute intervals throughout each run. Figure 4 shows three examples of these long signals, taken from the same reel as those of Fig. 3. Thus this figure, like the preceding one, shows the conditions obtained when negative temperature gradients produce an acoustical shadow zone near the surface within 800 yards range.

At short ranges (Fig. 4A) there are changes in amplitude at irregular intervals, occurring over periods of from 0.1 second to perhaps 5 seconds. At intermediate ranges, but still in the direct sound field (Fig. 4B), the variations in amplitude are much slower, lasting perhaps 8 seconds. Finally, at long ranges within the acoustical shadow, there are very rapid changes (Fig. 4C) which have very much the incoherent character of a reverberation record, in contrast to the changes in the direct field, which bear no resemblance to reverberation but are strongly coherent.

It is also apparent from Figs. 4A and 4B (and even more so when the complete record is viewed at once) that within the direct sound field the short signals are practically segments of the long signals. This might be expected from the absence of any appreciable "tail." The mean amplitude of the long signal is practically the same as that of the short ones, and the time sequence of amplitudes is the same. The relation between the long and short signals is quite different in the shadow zone as illustrated in Fig. 4C. Although both are strongly incoherent and have "tails," the mean amplitude of the long signal is greater than that of the short signal. This effect amounts to as much as 8 db in a typical case, at the range where the long reverberent "tail" is most prominent (see Figs. 3C and 3D); at longer ranges the difference decreases toward zero. It is probable that the long signal could be represented by superposing many short signals (inclusive of "tail") but the short signals are definitely not segments of the long transmissions.

Typical Records at Sonic Frequencies (0.2 to 7.5 kc)

Figures 7 and 8 show typical oscillograms of transmitted signals obtained at sonic frequencies.[2] For comparison with the high frequency work, data was also taken at 22.5 kc. The measurements were made in deep water (1000 fathoms) under conditions of moderately strong downward refraction, the range of the shadow boundary at hydrophone depth (50 feet) being about 1400 yards.

The general characteristics of the 24-kc signals are seen to be duplicated by the 22.5-kc transmission. At the lower frequencies, however, there are very noticeable differences in the general appearance of the traces, particularly for the long signals. Thus Fig. 8A shows a gradual increase in the rate of fluctuation of the long signals with frequency, the range being 125 yards. At longer ranges in the direct sound field the low frequencies tend to fluctuate more rapidly than the high frequencies, as shown by the 0.6- and 1.8-kc traces (although this is not always true, as shown by the 0.2-kc trace). Within the shadow zone the traces at all frequencies show a reverberation-like character, with a slow fluctuation of the envelope and a rapid fluctuation (distortion) of the amplitude, the rate of both increasing with frequency. (The serrated appearance of the background noise and signal on the 0.2-kc trace in Fig. 8B and C is caused by the action

[2] UCDWR, *Interim Report: Transmission of Underwater Sound at Lower Frequencies* (UCDWR U362, November 1, 1945).

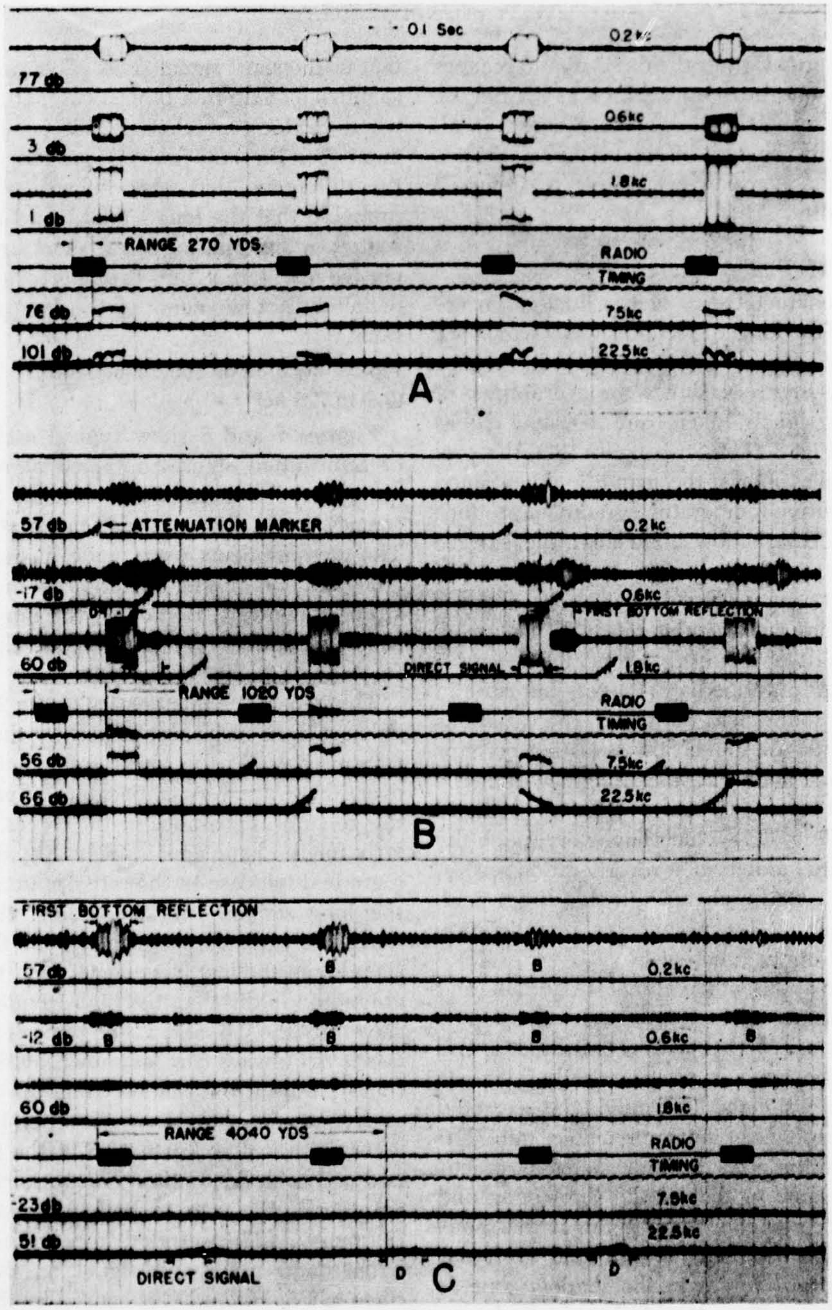

FIG. 7. Sonic signals, range 270 to 4000 yards, deep water.
Examples of deep water transmission record (short pulses).
Serial No. 433. March 21, 1945. Water depth: 1000 fathoms. Hydrophone depth: 50 feet.

of the receiver and is not observed when sufficient attenuation is in the circuit to reduce the background noise to an unreadable amplitude.)

Transmission in Shallow Water

Figures 9 and 10[2] reproduce records obtained in shallow (70 fathom) water over a rock bottom. The fluctuation of successive pings or of long signals is strikingly different from that in deep water. The short signals (Fig. 9) are seen to fluctuate widely at all frequencies and all ranges. It should be pointed out that the direct and bottom-reflected signals (D and B) almost overlap in

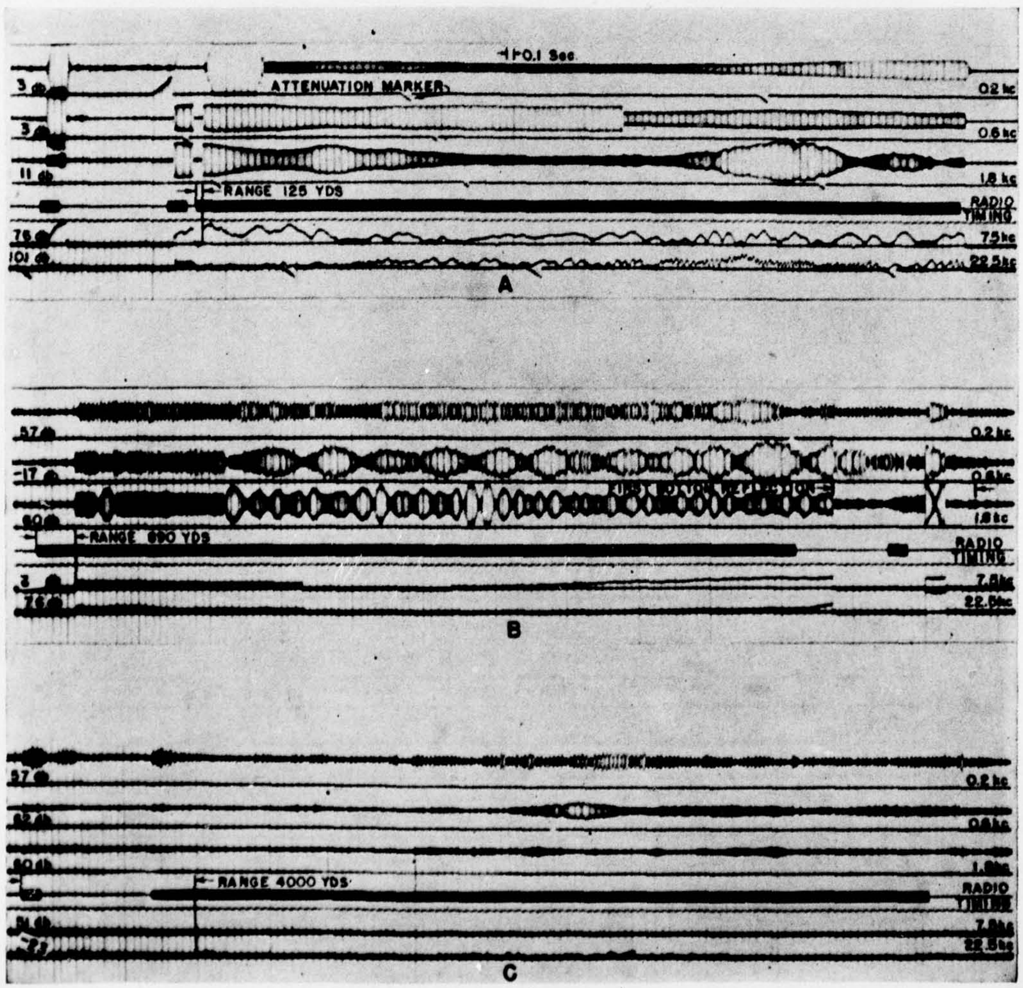

Fig. 8. Long sonic signals, range 125 to 4000 yards, deep water.
Examples of deep water transmission record (long signals).
March 21, 1945. Water depth: 1000 fathoms. Serial No. 433. Hydrophone depth: 50 feet.

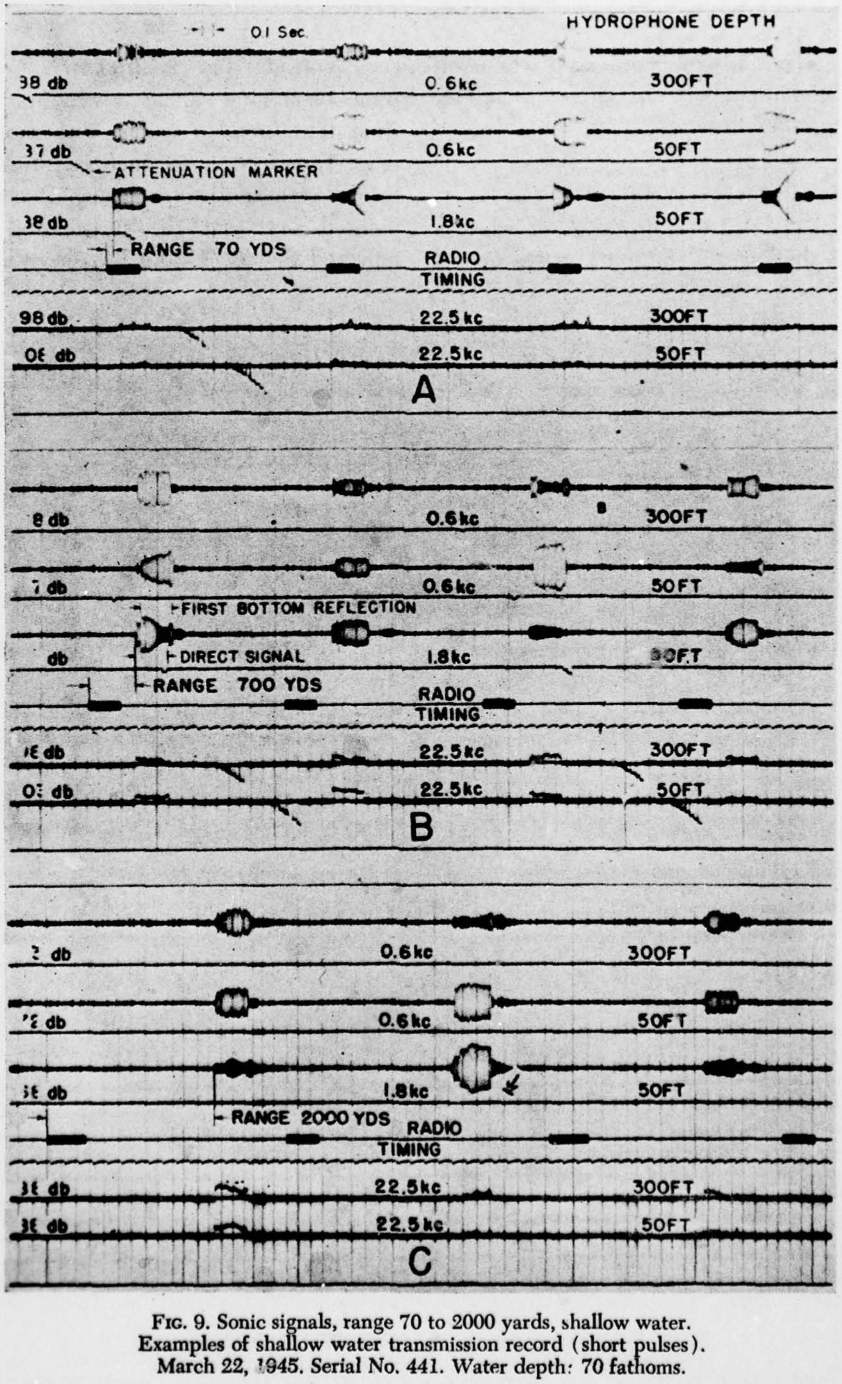

FIG. 9. Sonic signals, range 70 to 2000 yards, shallow water. Examples of shallow water transmission record (short pulses). March 22, 1945. Serial No. 441. Water depth: 70 fathoms.

Figs. 9B and C. In Fig. 10 the long signals show rapid fluctuation at short ranges (130 yards) and a slower fluctuation at longer ranges (800 and 1800 yards). At all ranges the rate of fluctuation increases with frequency, the effect being greater at long than at short ranges.

Time Scale of Fluctuation

It is useful to introduce certain terms to describe the obvious differences in the oscillograms reproduced in Figs. 2 and 3.

Distortion. The amplitude of a short signal may change or the amplitude of a short segment of a long signal may change during a

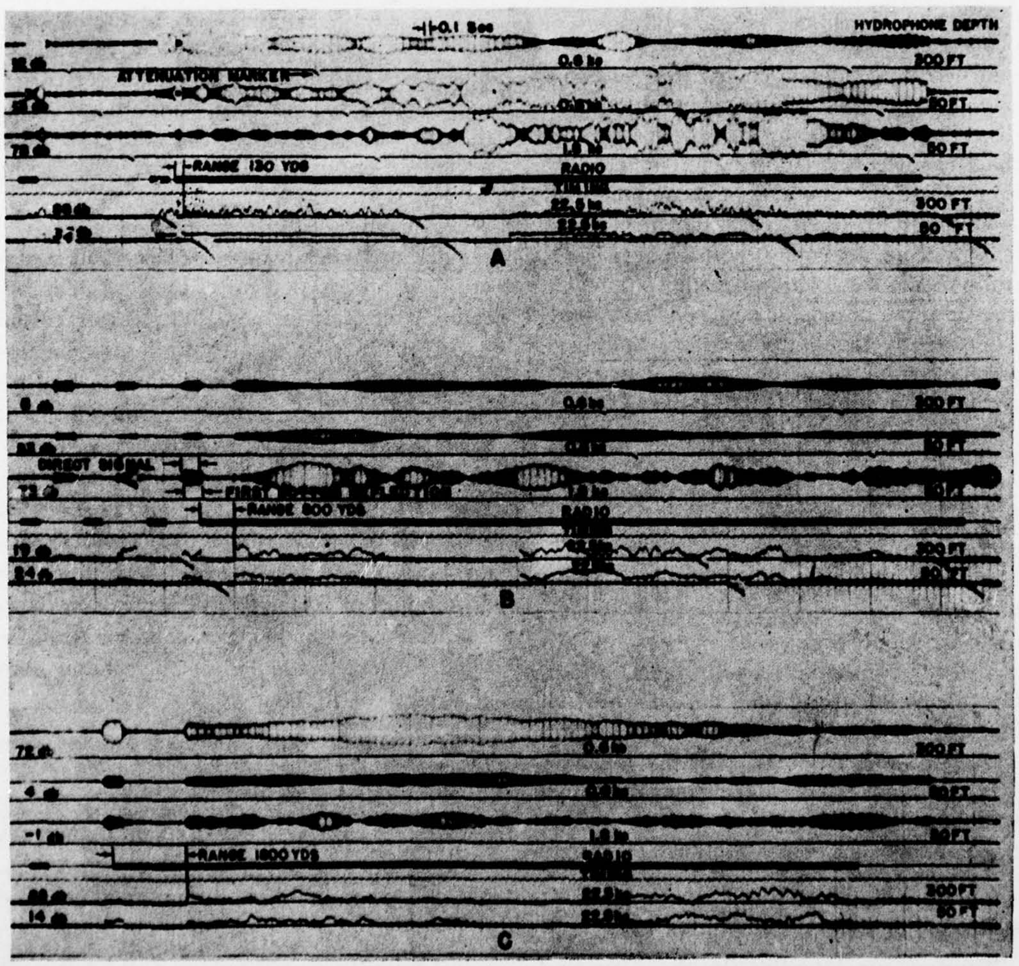

FIG. 10. Long sonic signals, range 130 to 1800 yards, shallow water. Examples of shallow water transmission record (long signals). March 22, 1945. Serial No. 441. Water depth: 70 fathoms.

time less than 0.1 second; this will be called distortion. Distortion is particularly noticeable in shadow zones where the amplitude may change by a factor of two or three in 0.05 second. At moderate ranges, within the direct sound field, this factor is considerably less, and at very short ranges (13 feet) the effect is practically non-existent.

Fluctuation. There may be changes in the average amplitude of successive short pings, or of successive short segments of long pings; this will be called fluctuation. It is especially apparent at moderate ranges, where there is little distortion. It also occurs at longer ranges, but then it is necessary to average out the distortion before the fluctuation becomes obvious.

Variation. Although not shown by Figs. 2 and 3, there are still slower changes in the transmission loss, which becomes appreciable in a half-hour or more. These become apparent when the average amplitude of a number of pings at one time is compared with that of another set received at a later time. The range should, of course, be the same for both sets. These slow changes will be called variation. The term variation is also used to designate differences in transmission loss measured under similar thermal conditions on different days.

It should be emphasized that these definitions are based entirely on their practical usefulness in discussing the experiments. Most of these were performed with signals of duration about 0.1 sec.—hence the choice of this figure as the dividing line between fluctuation and distortion. The usual duration of an experiment was of the order of magnitude one-half hour—hence the choice of this as the dividing line between variation and fluctuation.

Magnitude of the Fluctuation at 24 kc

Turning our attention to the manner in which successive pings differ from each other, we have seen that when pings of about 100-millisecond duration and constant amplitude are projected at intervals of a few seconds, the average amplitude of one ping will, after transmission, differ from the average amplitude of its neighbors. This effect is very clearly shown by the oscillograms of Fig. 9. Its quantitative aspects are illustrated by Fig. 16, A and C, on which the average amplitudes of 100 successive pings, received at half-second intervals, are plotted as ratios to the average amplitude of all 100 pings. These fluctuations can be dealt with quantitatively by the use of quantities common in statistical procedures; in particular, the variance, standard deviation, quartile and deciles, and the auto-correlation coefficient are useful. This last is used in Fig. 16, B and D.

The magnitude of the fluctuation of received signal amplitudes is described by their standard deviation, in percent of their mean amplitude. A set of 50 or more signals, all received within a few minutes, is usually used in this calculation. In this section we shall summarize existing information concerning the effects of various factors on the magnitude of the fluctuation. Most of the data were taken at San Diego by the Echo-Ranging Section of UCDWR and were reported.[3-7] These experiments were usually made in deep water using 24-kc pings of 50 to 100 milliseconds in duration, the projector being a standard Rochelle salt transducer, mounted on the sending ship at a depth of 16 feet.

[3] Echo-Ranging Section, *Amplitude Fluctuations of Transmitted and Reflected Sound Signals in the Ocean* (UCDWR A29, August 17, 1944).

[4] Sonar Data Division, *Transmission of 24 KC Sound at Short Ranges* (UCDWR M421, May 20, 1946).

[5] Sonar Data Division, *Transmission of 24 KC Sound from a Deep Projector* (UCDWR M409, April 8, 1946).

[6] Sonar Data Division, *Fluctuation of 24 KC Signals at Short Range as a Function of the Roll of the Sending Ship* (UCDWR M386, Dec. 11, 1945).

[7] Echo-Ranging Section, UCDWR, *Variability of Deep Water Transmission* (UCDWR, A40, October 5, 1944).

Average Magnitude

In a lengthy study[3] the standard deviation of amplitudes was calculated for each of 114 sets of 24-kc pings, the signals being 10 to 100 milliseconds long. The 114 deviations were found to vary from 20 percent to 70 percent and to have a mean value of 42.3 percent of the mean amplitude, with a quartile deviation of 7.5 percent.

Dependence of Fluctuation on Refraction Conditions

The only reported investigation of the influence of oceanographic conditions on the fluctuation at 24 kc has been carried out by UCDWR at San Diego.[2] It was found that the fluctuation of the direct sound is slightly smaller for downward refraction than for isothermal conditions. Although this effect is small, statistical tests indicate that it is significant. Since several sample sequences were available, it is possible to speak of the median standard deviation, which is defined as that value of the standard deviation which is exceeded in half of the sample sequences. The following results were found: The median standard deviation was 38 percent for strong downward refraction and 36 percent for weak downward refraction. For mixed layers there was a difference between measurements made above and below the thermocline. The median standard deviation was 41 percent for measurements made with the hydrophone below the thermocline and 47 percent for measurements made above. It is not certain that this difference in the fluctuation above and below the bottom of the mixed layer is real. Later data (unpublished, UCDWR) fails to show the effect. About all that can be concluded is that there is no strong dependence of fluctuation on thermal pattern. Under some conditions the distortion of the signals above and below the layer are known to be different (see section on "Causes of Distortion").

Dependence of Fluctuation on Hydrophone Depth, Signal Length, and Range

Apart from the effect just mentioned for the mixed layer patterns, the magnitude of the fluctuation at 24 kc shows no dependence on hydrophone depth.[3] The projector depth in these experiments was 16 feet and the hydrophone depth varied from 16 to 400 feet. In the same set of data, no dependence was found on the signal length, which varied from 10 to 100 milliseconds, most of the data being taken with 50–and 60–millisecond pings. Nor was there any significant dependence found on range between 100 and 8000 yards, as shown by Fig. 11. The larger spread of the data at short ranges is probably due to the fact that more measurements were made at these ranges. (The fluctuation at less than 100 yards will be discussed in the following section.)

While this lack of dependence on three basic factors may seem surprising, there are several features of the data that should be kept in mind. First, the results refer to the average magnitude of the fluctuation, i.e., to the average standard deviation. In the case of ping length (50 milliseconds), for example, the 60 odd values of the standard deviation spread from 20 to 70 percent. A similar spread is found when the standard deviations are plotted against range. It is entirely possible, therefore, that a more detailed breakdown of the data might reveal a dependence on these factors. In particular, the presence of a systematic range dependence (see "Image effect") would almost certainly be obscured in such a statistical treatment of the data. Second, the results refer to the composite signal, consisting of both direct and surface reflected sound. As will be shown below, the fluctuation of the two components is quite different, and this difference is completely obscured in the above analysis. In this connection the use of shorter signals would certainly affect the fluctuation, since it would allow the two components to be sepa-

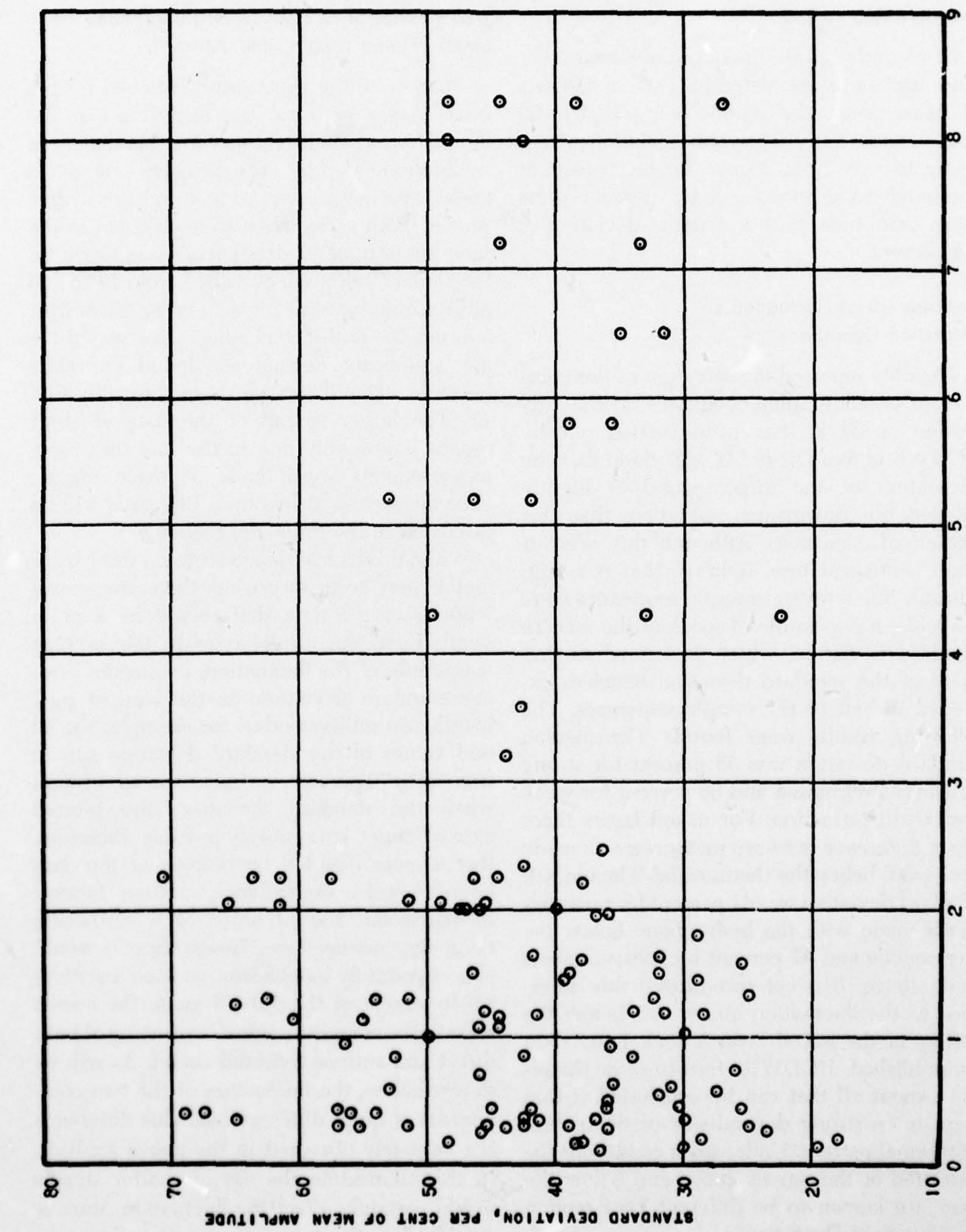

FIG. 11. Fluctuation as a function of range.

rated. Finally, as will become evident, the surface is by far the most important cause of fluctuation; yet in none of the various analysis has there been a correlation of the fluctuation with the statistical properties of the sea surface. This is due partially to the difficulty of obtaining oceanographic data for such studies, and also to the lack of time for such lengthy analysis. Thus the question of the dependence on these factors is still open.

Fluctuation of Direct and Surface-Reflected Sound

(a) A number of transmission experiments were made by UCDWR[5] using suspended projectors and hydrophones (overside at 16, 150, 300, 500, 1000 feet). Short pings (10- and 30-millisecond) at 24 kc were employed and the combination of deep transducers and short signals made it possible to resolve the direct and surface-reflected signals and study their fluctuation separately. The data were taken in the San Diego area under conditions of downward refraction near the surface. Refraction conditions at the deeper transducer depths (500 and 1000 feet) were not determined as the bathythermograph could not be lowered below 400 feet. The sea state was 0 or 1. The following results were found:

(1) The amplitude fluctuation of the direct signals increases with range. The standard deviation is roughly proportional to the square root of the range. This can only be considered a general trend, however, owing to the scatter of the data. The line of best fit rises from 6 percent at 40 yards to 50 percent at 3000 yards. Between 200 and 500 yards the standard deviation was 20 percent, projector and hydrophone being at the same depth (150 to 1000 feet); no significant dependence on depth was found.

(2) The fluctuation of the surface-reflected signals does not depend on range or hydrophone depth; the average value of the standard deviation is 48 percent. Part, but by no means all, of this increase in fluctuation over that of the direct signals could be due to irregularities of the transducer patterns in planes inclined at an angle to the horizontal.

(3) The correlation between the amplitudes of the direct and surface-reflected signals decreases with transducer depth and is negligibly small for depths of 300 feet or more.

(4) Direct sound often reaches the hydrophone via several paths.

(b) A similar investigation was made by Naval Research Laboratory using a deep source mounted on a submarine at a depth of 200 feet.[8] Extremely short (1/2-millisecond) square-top signals were emitted at a rate of 50 to 100 per second, at a frequency of 25 kc. These were received on a hydrophone at a depth of 12 feet, mounted on a surface ship. The experiments were made in an isothermal layer 300 feet thick with a choppy sea. Examination of the oscillograms shows that:

(1) The signal was received as a sequence of two to six pulses. The direct signal was no longer square-topped but varied smoothly, having one or two maxima. The reflected sound consisted of a primary pulse followed by several smaller secondary pulses of amplitudes from 1/2 to 1/4 of the primary amplitude.

(2) The arrival time of the primary agrees with that to be expected if it were reflected specularly from a mirror surface. The average ratio of the amplitude of the reflected signal, to that of the received direct signal, is 0.8.

(3) Fluctuation of surface-reflected waves is far greater than that of direct waves.

(4) No correlation was observed between

[8] R. J. Urick and H. L. Saxton, "Surface reflection of short supersonic pulses in the ocean," J. Acous. Soc. Am. 19, 8 (1947).

ship motion and fluctuation, nor between the relative direction of surface and sound waves and the resulting fluctuation.

It is suggested that the reason for the departure from unity is that the sound is reflected from curved sections of the sea surface, which introduces an added divergence and a correspondingly lower amplitude. It also seems that the surface reflection is not very diffuse, since this would give rise to a long irregular blob rather than the observed individual pulses of duration comparable to the original length.

(c) Finally, there is evidence obtained by UCDWR while studying the transmission of 24-kc sound at short ranges of from 7 to 180 yards.[4] The experiments were performed in 12- to 14-fathom water in the lee of the South Coronado Island, under thermal conditions which produced downward refraction. Although the water was shallow, bottom-reflected sound did not influence the transmission at these short ranges. The sea surface was relatively calm, sea state varying from 0 to 2, and the wind force from 1 to 3 on the Beaufort scale. Swell heights ranged from 1 to 3 feet. Projector and hydrophone depths were 16 feet. The following results were found:

(1) Under fairly calm and well-controlled experimental conditions, but with a swell of 1 to 3 feet, there was no evidence of a systematic surface-image pattern, although there was evidence that surface-reflected sound caused a slight decrease in the transmission anomaly, i.e., improved the transmission slightly.

(2) This slight decrease in the transmission anomaly agreed fairly well with a calculated value, assuming a surface reflection coefficient of 0.7 and assuming that the received signal is composed of a direct signal of constant amplitude (in time) and a large number of surface-reflected components of small amplitude and random phases. (See page 109 for a discussion of this theory.)

(3) The average fluctuation of the direct signal was very small from 7 to 40 yards. At 40 yards, the surface-reflected sound became appreciable. From 40 to 100 yards the fluctuation increased rapidly from about 7 percent to 40 percent, in good agreement with the value calculated from the above assumptions. Beyond 100 yards the average fluctuation did not change, in agreement with the results on page 81.

Dependence of Fluctuation on Image Effect

While the image effect is observed only rarely at 24 kc, it is known to be a dominant feature of the transmission at lower frequencies[2, 9] and therefore an important cause of fluctuation. Even at the high frequencies it is clear that the surface-reflected sound is a major cause of fluctuation. In addition, much of the theoretical work on fluctuation has been prompted by considerations of the image effect. For all of these reasons it is of interest to review the experimental evidence obtained at the higher frequencies.

As pointed out in the previous section, the interference pattern caused by the interference of the direct and surface-reflected sound is usually not observed at 24 kc, even with a relatively calm sea and slight swell. This is because small variations in the geometry, caused by motion of the projector and receiver and by deviations of the surface from a plane, are sufficient to introduce path differences large in comparison to the wavelength (2½ inches) of 24-kc sound. Nevertheless, with a flat calm and no swell the image pattern has been observed at high frequencies.

(a) Figure 12 shows a record taken by UCDWR in San Diego Harbor, using 20-kc

[9] R. W. Young, "Image interference in the presence of refraction," J. Acous. Soc. Am. 19, 1 (1947).

sound and very shallow transducers.[10] The solid curve is the calculated intensity, assuming the surface to be a flat mirror.[11] The average measured intensity is seen to be a good agreement with the predicted pattern. The departures of the instantaneous measurements from the theoretical curve, however, are most striking. They are due to time variations in the intensity of the sound, rather than to space variations. The amplitude of these fluctuations, expressed in db, is seen to be greatest at the places where, theoretically, there should be a minimum. These phenomena can all be explained by supposing that the amplitudes of the direct and reflected sound remain constant, while their phase difference varies in an irregular manner by several radians. The assumed variation in phase angle can be accounted for by the vertical motion of the hydrophone, which was mounted on a small boat.

It appears, therefore, that under the ideal conditions of this experiment, there existed a virtually perfect interference pattern in space, and that the fluctuations in the observed intensity were due to motion of the hydrophone. It should be noted that the range was very short, the entire pattern shown extending only from 20 to 90 feet.

(b) Some experiments were made by WHOI[12] to study the space pattern of intensity at short ranges. In order to eliminate the motion of source and receiver, the transducers were mounted on two steel towers embedded in the ocean bottom. The towers were located about 150 feet apart in 44 feet of water, and the transducers were mounted about 10 feet below the surface. The transmitted signals were short, frequency-modulated pulses. Each

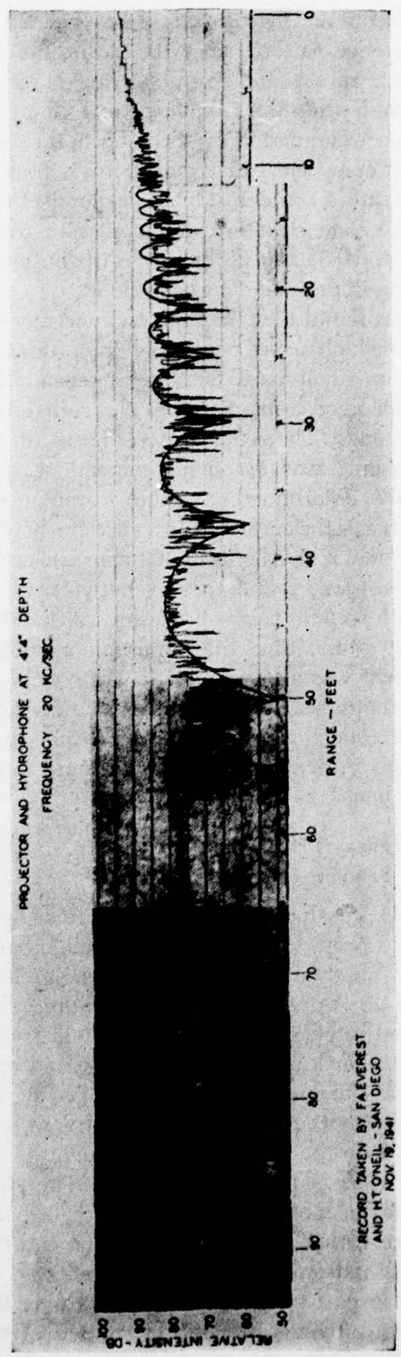

FIG. 12. Surface image effect, frequency 20 kc.

[10] R. R. Carhart, *Lloyd Mirror Effect in a Variable Velocity Medium* (UCDWR M140, October 23, 1943).

[11] H. T. O'Neil and T. F. Johnston, *Variation of the Sound Field Near the Surface in Deep Water* (UCDWR U49, March 16, 1943).

[12] L. N. Liebermann and A. J. Yaspan, *Reflection of Sound from the Sea Surface* (WHOI, Rep. No. 30, October 1946).

such frequency sweep (27-33 kc) yielded an interference pattern, since the path difference between direct and surface-reflected sound was fixed while the frequency was changing; from an examination of the interference patterns of many successive pulses, it was possible to obtain (1) the instantaneous reflectivity, (2) the time structure of changes in reflectivity, and (3) the probability distribution of the amplitude reflection coefficient.

It was found that the reflectivity at any one frequency changed negligibly in a time interval as small as 1/30th of a second, but often changed appreciably in the course of a few seconds. The reflection coefficient at any one instant was frequency-dependent, presumably determined by the instantaneous geometry of the surface. With all wave heights up to one foot, the instantaneous reflection coefficient was found to vary between 0 and 2.5, with median values near unity. At least 10 percent of the time the amplitude reflection coefficient was above unity. It was concluded that a rough sea surface reflects sound as if it were a collection of separated distinct small mirrors, so oriented as to deliver sound to the hydrophone.

Dependence of Fluctuation on Roll of Sending Ship

At 24 kc the sound beam emitted by a standard projector is highly directional, being a cone of about 6 degrees half-angle. It is natural to suppose that as the sending ship rolls and pitches the sound beam will sweep back and forth over the hydrophone and contribute to the fluctuation of the received signal. Early attempts to study this effect were concerned with the accurate measurement of the actual beam pattern in the water. The state of the art of measuring the short range sound field was rather primitive at the time and the irregular patterns observed were believed to be due in part to the lack of control over the yawning, pitching, and rolling motion of the sending ship, and to parallax in the training system. Later, with improved equipment, the experimental work was resumed.[6] This work will be described in some detail for three reasons: (1) It is one of the few experimental studies designed explicitly to investigate fluctuation; (2) the data furnish some significant facts concerning the relative fluctuation in the direct and surface-reflected sound; (3) a large amount of accurate data was obtained, only a small amount of which have been analyzed, so that there is a valuable fund of fluctuation data available.

Some idea of the experimental complexity of accurate measurements at short range may be gained from a summary of the improvements which consist of: (1) placement of the training pelorus directly over the projector to eliminate training parallax; (2) elimination of backlash in the projector training gear; (3) construction of a selsyn repeater panel giving continuous presentation of ships' roll, pitch, ship heading, projector heading, and target (i.e., pelorus) bearing. The panel also contained a clock and an electric counter and was automatically photographed by an electrically operated camera at the instant each ping was emitted.

The data were taken in deep water with sea states 0-1 at ranges of 100 or 200 yards, the ships being tied together with a heavy line to prevent any appreciable changes in range during the runs. The projector was at a depth of 16 feet and three hydrophones were set at constant depths: one at projector depth; the second at depths corresponding to five or six degrees below the projector; and the third at various depths down to about 30 degrees below the projector. For each set of hydrophone depths the projector heading was varied, at intervals of 5 degrees, from directly towards the hydrophones to 30 degrees on either side. At each projector setting 24-kc signals were emitted at regular one-second intervals.

During the two-day operations, 145 sets of signals were recorded, averaging about 75 signals per set. Complete analysis of approximately 33,000 recorded signal amplitudes with accompanying data on ship orientation was not attempted. A study was made only of the fluctuation of the signals received with the projector directed toward the hydrophone position. For these data the projector heading relative to the sending ship was always within a few degrees of 90 or 270 degrees; hence the pitch of the ship can be ignored, and the vertical angle of the projector is given by the angle of the roll. Thus the data refer to the intensity in the vertical plane through the projector axis.

The results of this study were as follows:

(1) When the hydrophone was at the same depth as the projector, the fluctuation of the signal amplitudes showed no significant dependence on the roll of sending ship. The mean standard deviation at this depth was 40 percent.

(2) When the hydrophone was 6 degrees below the projector, fluctuation depended on roll only when the roll was more than 2 degrees.

(3) When the hydrophone was between 13 and 31 degrees beneath the projector, the fluctuation depended on roll only when the roll was more than 4 degrees.

(4) When the roll exceeded the angles mentioned in (2) and (3), the fluctuation increased while the projector was tilted up toward the surface and decreased while tilted down away from the surface. The total change in the standard deviation varied from 11 percent to 33 percent.

It can be concluded, therefore, that the amplitude fluctuation of 24-kc signals received at short range is affected by the roll of the sending ship in a manner that can be understood if it is assumed that the surface reflected sound contributes significantly to the total fluctuation.

The Distribution Function of the Signal Amplitudes

Figures 13, 14 and 15 show typical distribution functions of the signal amplitudes. In each case, the empirical data are compared with the graphs of two formulae. The Rayleigh formula is expected to apply if the received sound is the resultant of numerous waves of small amplitude and random phase. It contains only one parameter—the mean amplitude —and the standard deviation calculated from it is 52 percent. The Gaussian formula has no theoretical foundation and was used in order to have two parameters free for obtaining a fit to the data. The figures show that neither of the formulae always fits the data.

Coherence of Fluctuation at 24 kc

One of the most striking features of fluctuation is the fact that the rapidity of fluctuation shows an obvious and marked dependence on the range, while the magnitude of fluctuation, apart from short-range effects due to transducer directivity patterns shows no significant dependence on range whatever.

The rapid, reverberation-like fluctuation or distortion observed in the shadow zone has been discussed on page 69; in "Causes of Distortion" it will be shown to be caused by scattering from the volume of the sea. In this section we shall consider the quantitative aspects of the decrease in the rapidity of fluctuation with range, which is observed in the direct sound field. This phenomenon will be considered as a coherence of fluctuation in time, since it correlates the amplitudes of successive pulses. It is also possible to study the correlation between the amplitudes of pulses received simultaneously at adjacent positions, i.e., the coherence of fluctuation in space. Evidence of this type will also be summarized. Finally, one can examine the coherence of fluc-

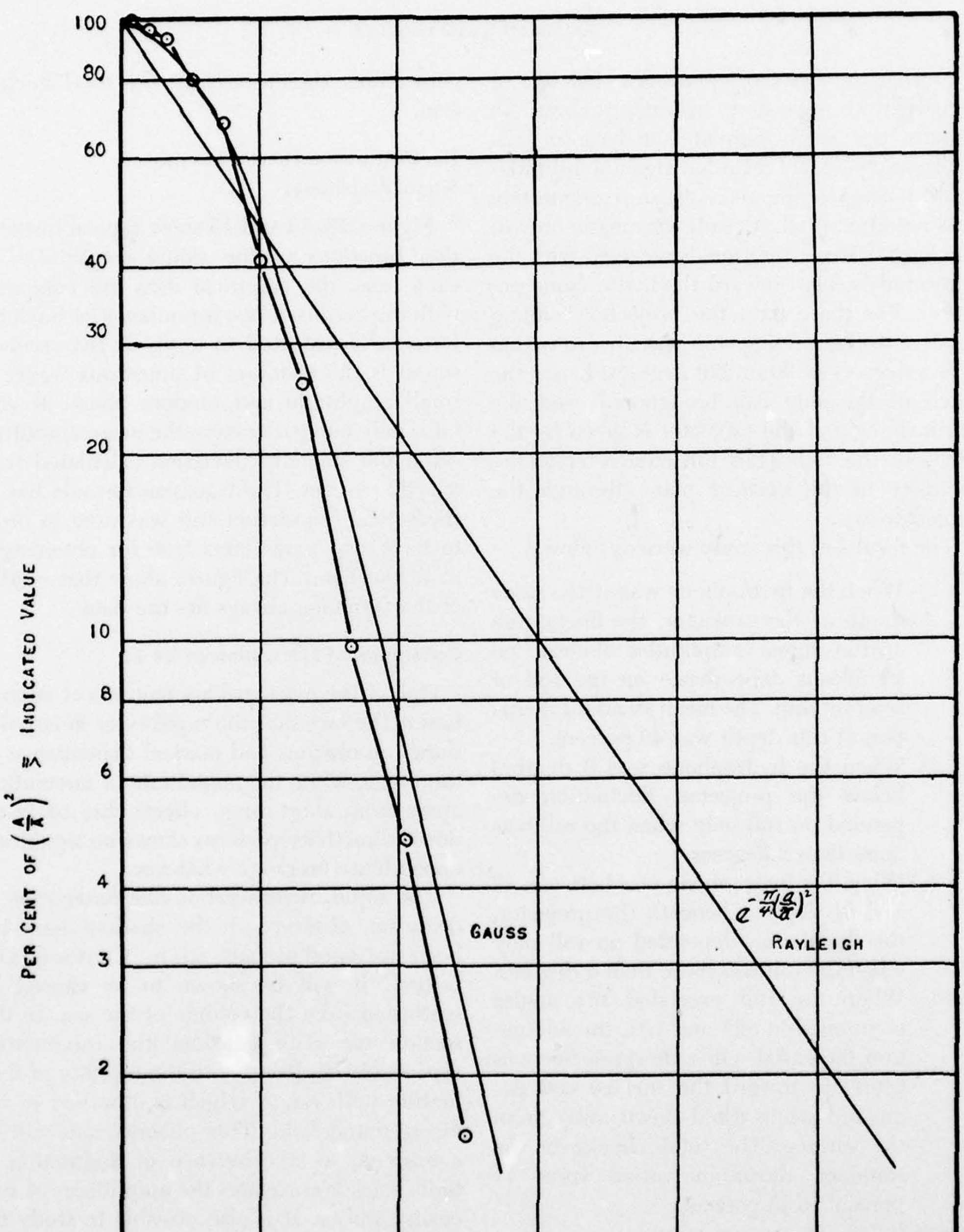

FIG. 13. Cumulative distribution of amplitudes, range 60 yards.

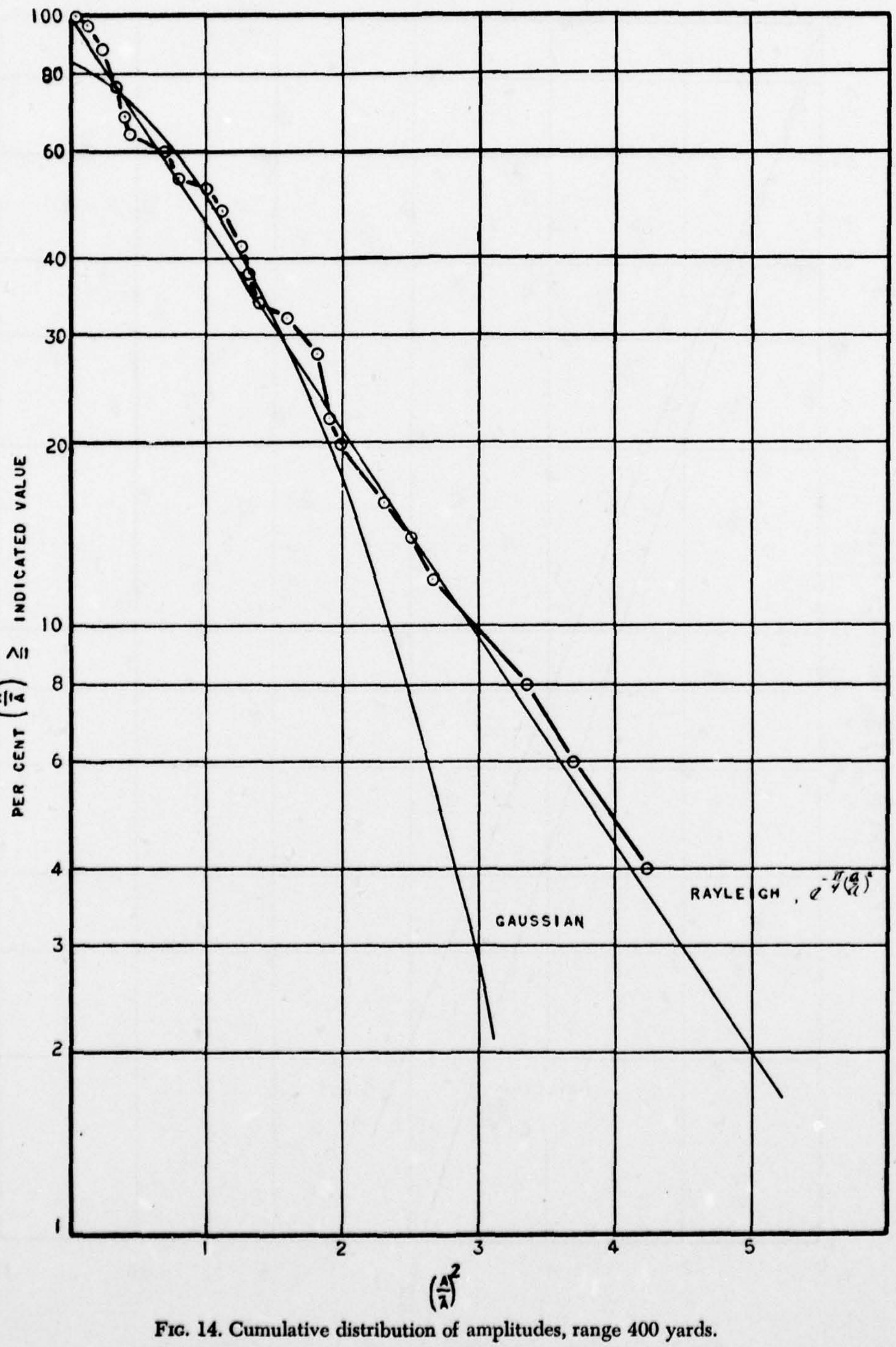

FIG. 14. Cumulative distribution of amplitudes, range 400 yards.

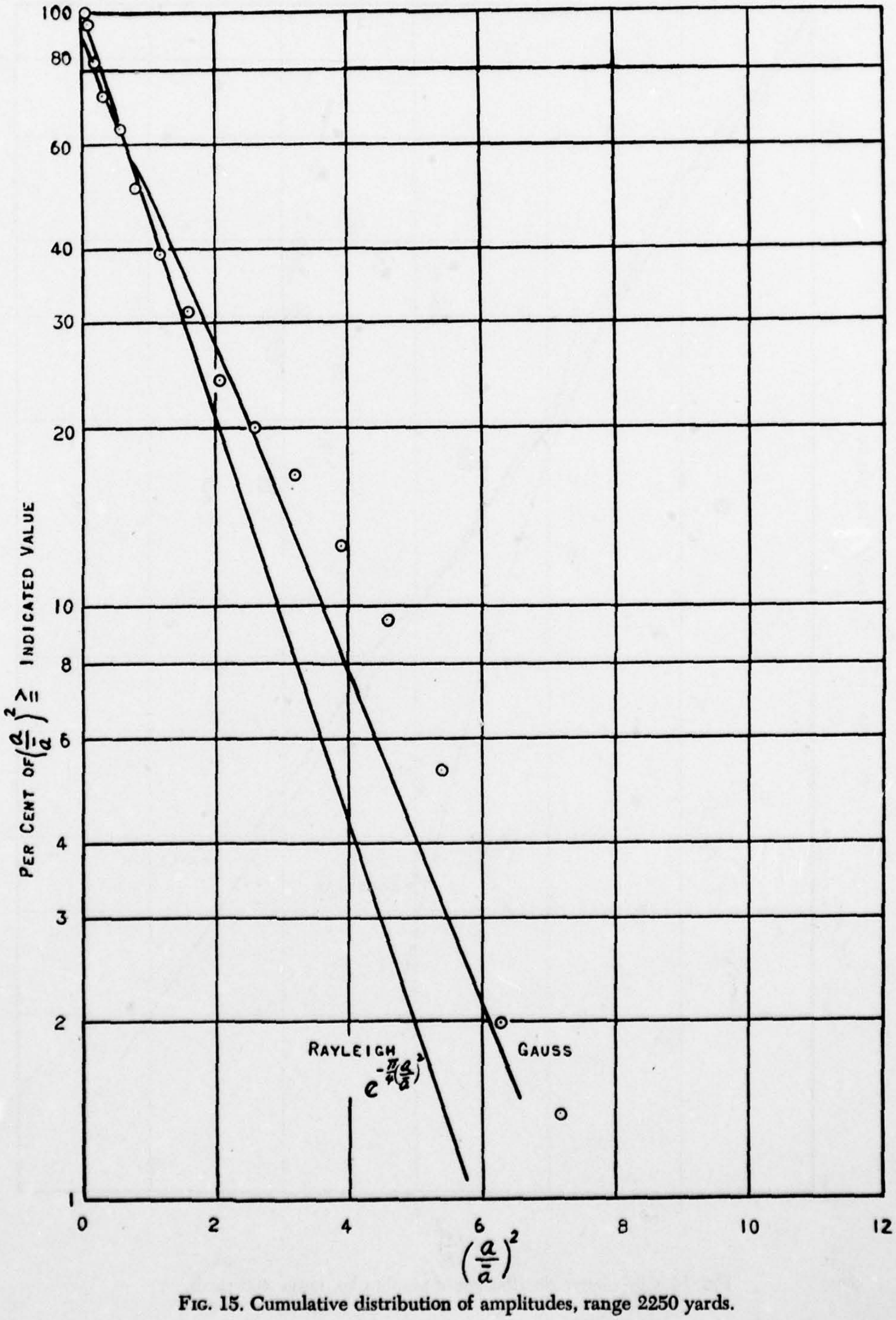

Fig. 15. Cumulative distribution of amplitudes, range 2250 yards.

tuation in frequency by studying the signals received simultaneously at two frequencies or by studying frequency-modulated signals, as will now be discussed.

Auto-Correlation Studies: Successive Signals Received on the Same Hydrophone

Figure 16 shows the decrease in the rate of fluctuation with range. In the graphs A and C about 100 successive received amplitudes are plotted for each of two mean ranges, 115 and 980 yards, both positions being within the direct sound field. The signals were 55 milliseconds long and were emitted every half-second. The depths of projector and hydrophone were 16 and 25 feet, respectively. Inspection of graphs A and C shows that there is a difference in the rate at which the amplitude changes. In A, a high amplitude signal is as likely to be succeeded by a low one as by another high one; the fluctuation is thus practically random, any one signal being statistically independent of its predecessor. In C, on the other hand, a high amplitude signal is much more likely to be succeeded by another one above average than by one that is below average.

The rate at which the signal amplitude fluctuates can be described by the auto-correlation coefficient (see Appendix). This coefficient describes the average agreement between pairs of signals separated by a given period of time (called the correlation interval). For example, if the interval corresponded to 4 signals, the auto-correlation coefficient would describe the average agreement between signals 1 and 5, between 2 and 6, etc. If the fluctuation were periodic with a period of 4 signals, the correlation coefficient would be + 1; if signals 1 and 5, etc., were just out of step (equal amplitudes but opposite in sign), the coefficient would be −1; and if, on the average, there were no correlation, it would be zero. A graph of the correlation coefficient thus gives information about the departures from periodicities on the one hand, and from perfect randomness on the other.

Examples of graphs of auto-correlation coefficients as a function of the correlation interval are shown in Figs. 16B and 16D. These graphs correspond respectively, to the graphs of the amplitude deviation of Figs. 16A and 16C and illustrate the foregoing remarks. In B the coefficient drops from unity within 0.5 second and thereafter is rarely greater than 20 percent; this indicates that the fluctuation shown in A is nearly random. In D the coefficient remains above 50 percent for 1.5 seconds, and drops to −50 percent at 8 seconds. This means that a high signal is followed by other high signals for 1.5 seconds, but after 8 seconds it is followed by unusually low signals. In A one can see smaller traces of 5-second and 8-second periods.

Figure 17 shows auto-correlation graphs at various ranges. These curves were obtained from the long signals recorded during the run of July 6, 1943 which has already been discussed (figs. 2-5). At 250 yards the correlation coefficient drops rapidly with increasing correlation interval, while at 650 yards, at the edge of the direct sound field, it drops much more slowly. These graphs are thus in accordance with the qualitative observation that the rapidity of the fluctuation decreases with range. Within the shadow zone, at 1100 and 3700 yards, the coefficient again drops rapidly, indicating an increase in the rapidity of fluctuation in agreement with the reverberation-like character of the shadow-zone signals. Thus the auto-correlation graphs provide a quantitative measure of the rapidity of fluctuation which is so evident in the original records.

The auto-correlation graph at 3700 yards (fig. 17) shows some evidence of a period of about 1 second, in contrast to the 8-second period shown by Fig. 16D. In both cases the sending ship was underway and the periodic motion, if it is real, is probably due to pitch.

A striking example of the periodic type of

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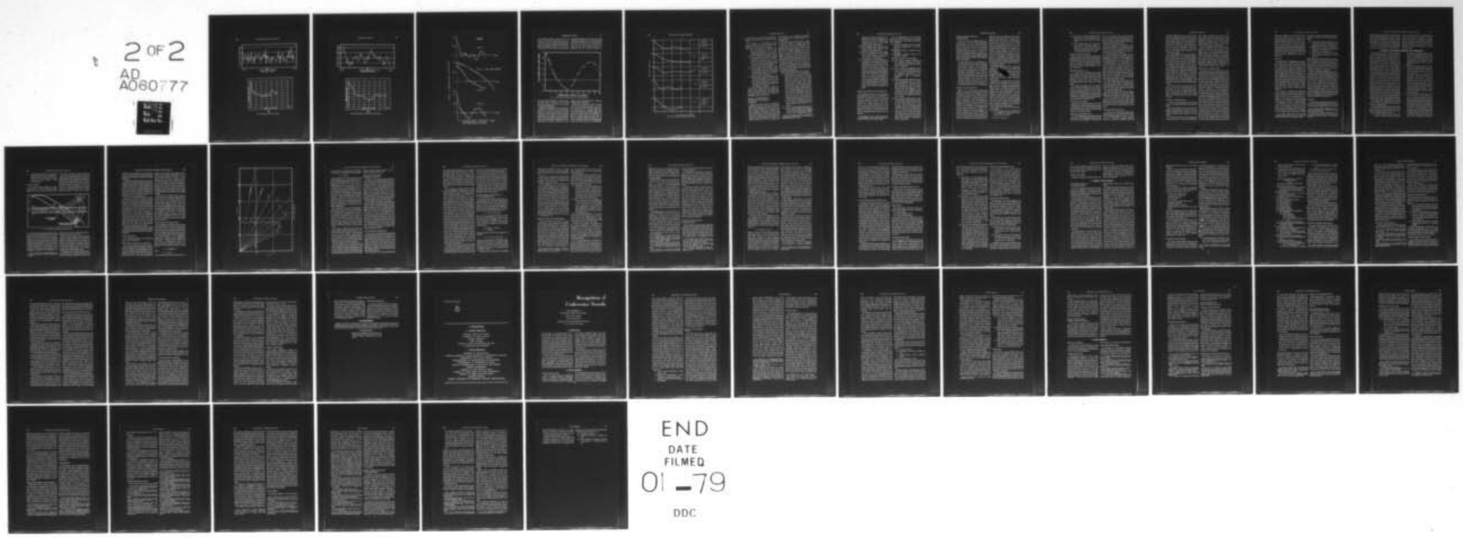

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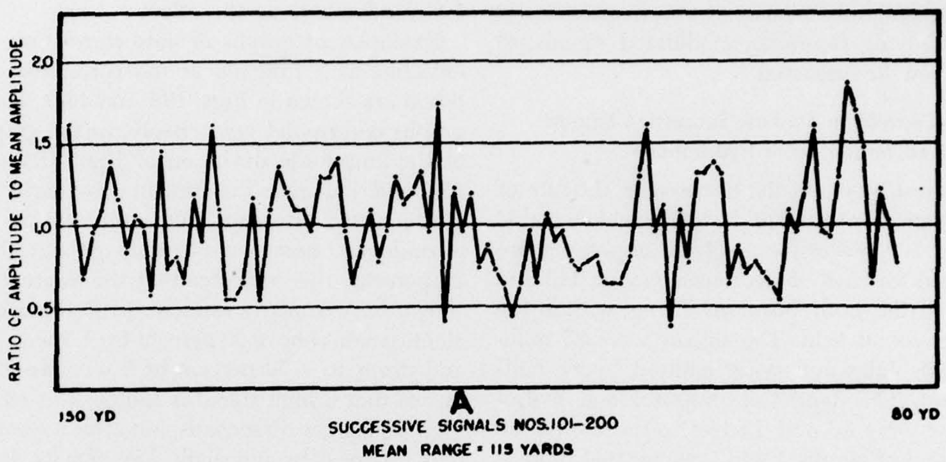


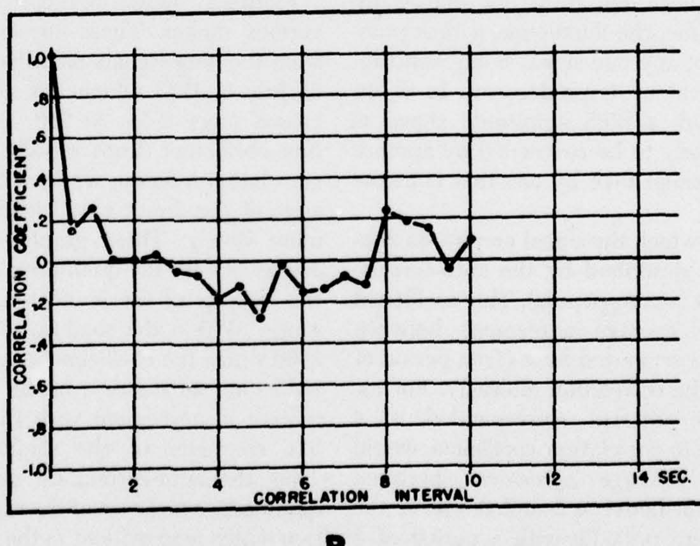
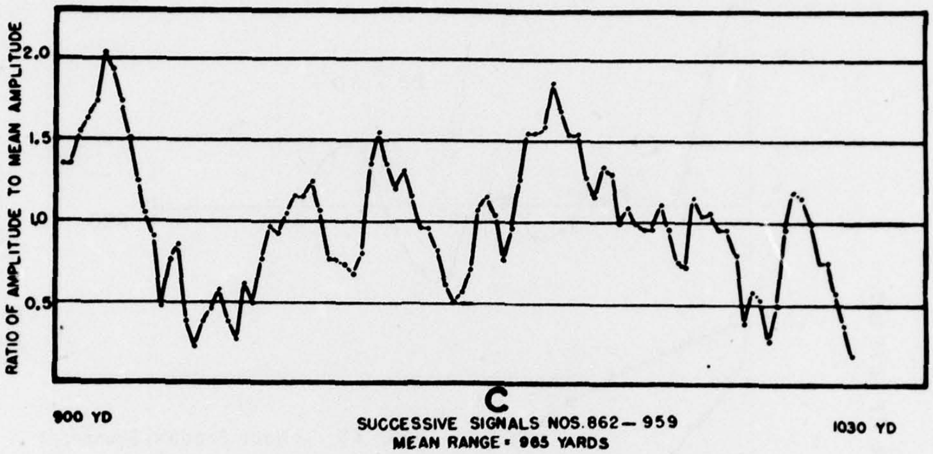


FIG. 16. Fluctuation and auto-correlation.



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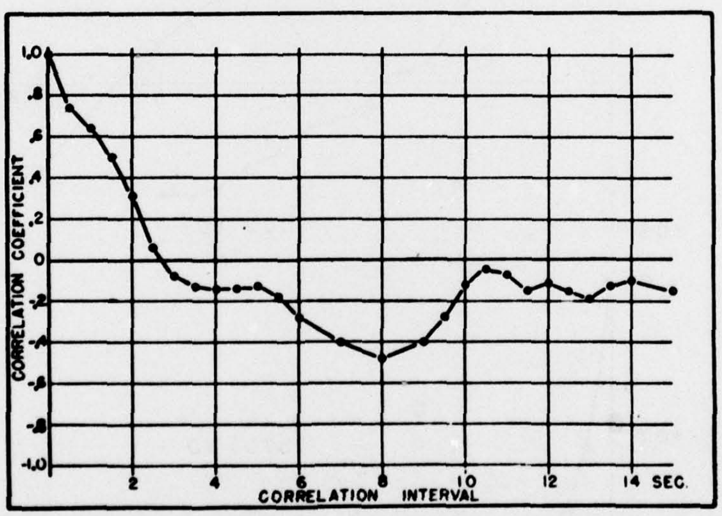

D

FIG. 16. Fluctuation and auto-correlation *(continued)*.

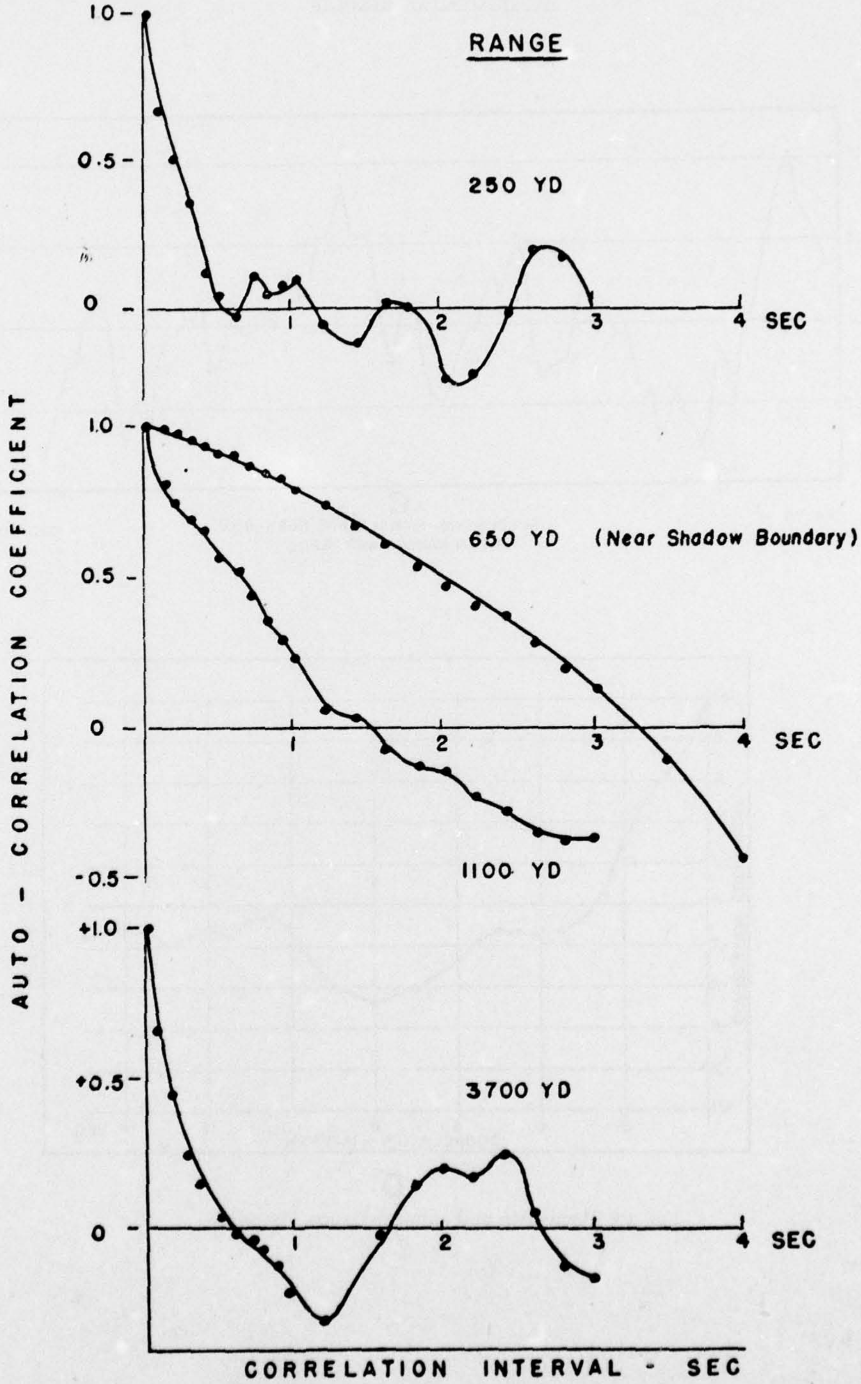

FIG. 17. Auto-correlation at various ranges.

auto-correlation graph is shown in Fig. 18. Successive pings 100 milliseconds long were received at a range of 8300 yards under very good transmission conditions with the hydrophone at a depth of 100 feet in a mixed layer 150 feet deep. The sending ship was lying to, its beam being towards the receiving ship. The graph shows evidence of an 8-second period, in agreement with the known period of roll of the sending ship.

While the periodicity shown in this graph is probably real, it should be pointed out that this type of coherence analysis is generally valid only if the correlation interval is short compared to the length of record analyzed. Thus a correlation interval of 10 seconds probably requires a 100-second record if the corresponding auto-correlation coefficient is to be statistically significant. In the data of Fig. 19 the longest correlation interval was 20 seconds and the record analyzed was 104 seconds or about 5 times as long as the interval. Thus while Fig. 19 seems convincing, there is a possibility that the periodic character is spurious. More theoretical study is required to settle this point definitely.

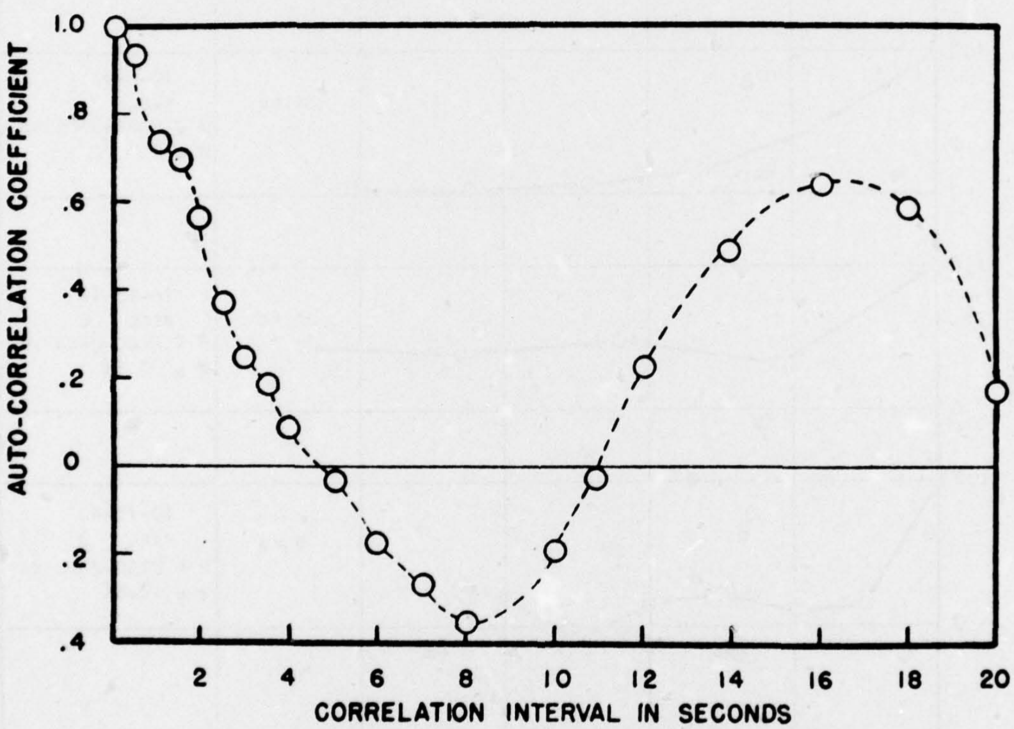

FIG. 18. Auto-correlation, showing a periodic effect attributed to roll.

Finally, Fig. 19 shows five more examples of the auto-correlation graphs for 5, 10, and 24 kc, given in reference 3. There appears to be no dependence on frequency. The data were taken at long ranges (1930 to 3400 yards) under very good transmission conditions so that the received signals consisted only of direct and surface-reflected sound, and not volume-scattered sound. Of these graphs, only the last one shows evidence of a periodicity,

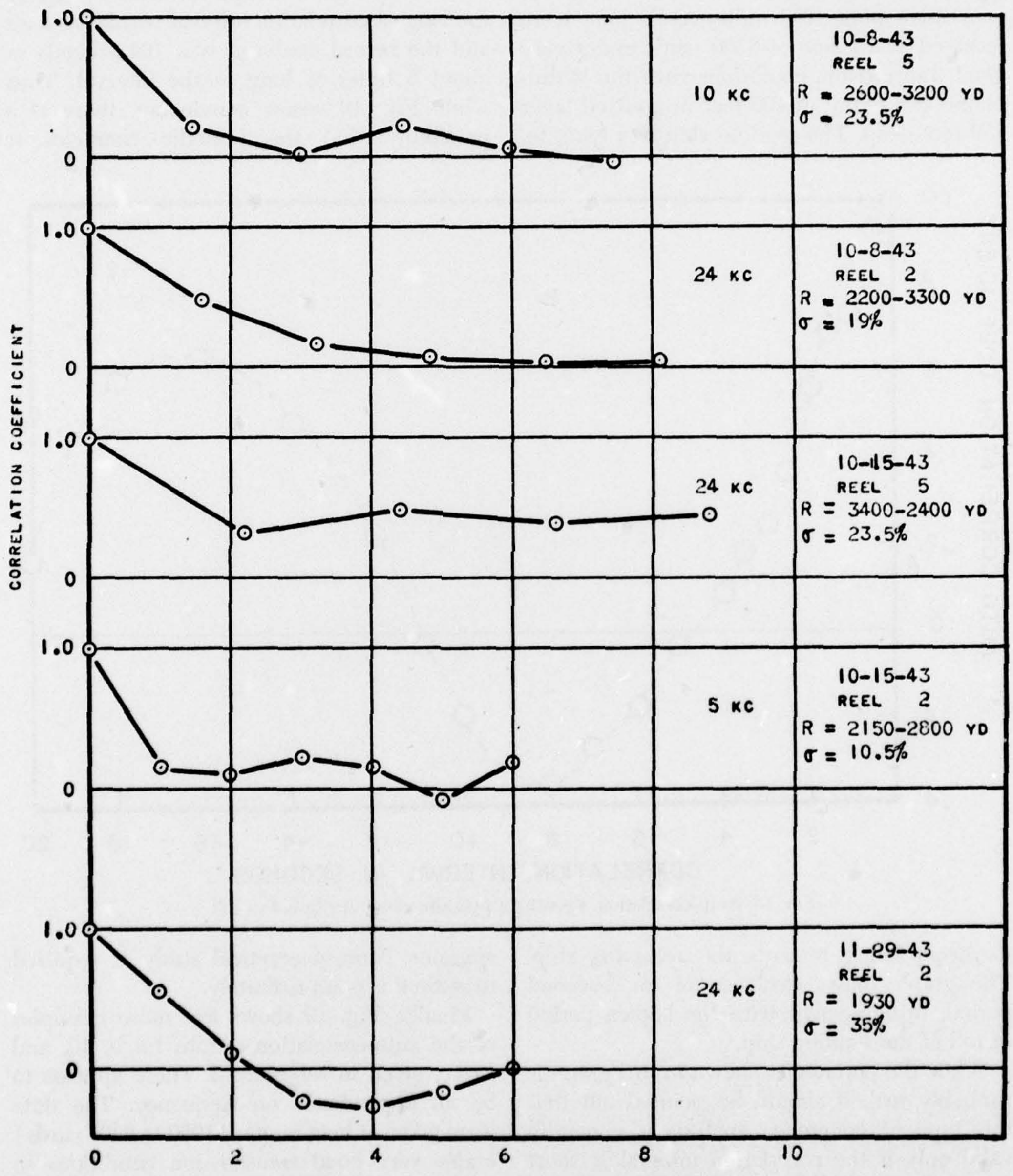

FIG. 19. Auto-correlation, frequencies 5, 10, 24 kc.

and this evidence is weak, since the minimum value of the auto-correlation coefficient is only −0.3.

These graphs are representative of the signals received in deep water. The principal features may be summarized as follows:

(1) The auto-correlation coefficient may drop monotonically to zero or may oscillate, dropping first to a negative value and then rising to a positive value.

(2) In some cases these oscillations appear to be too large to be due to statistical fluctuations, sampling errors, etc.; in some cases, they are probably caused by pitch and roll of the sending vessel, or by wave and swell periodicities.

(3) The time scale of the correlation coefficient expands with increasing range, corresponding to the slower fluctuation at long ranges which is so qualitatively apparent in the oscillograms.

(4) In the shadow zone the graphs have the same general appearance as those in the direct sound field, but the time scale is somewhat contracted, in agreement with the reverberation-like character of the shadow-zone signals.

No auto-correlation graphs are available for shallow water. Judging from the appearance of the transmission records, it is probable that the graphs would resemble those obtained in the shadow zone in deep water.

Correlation of Signals Received Simultaneously on Two Adjacent Hydrophones

Studies have been made by UCDWR in which 24-kc signals were received simultaneously on two hydrophones at the same range. The correlation between the amplitudes was then calculated. The object of the investigations was to determine the dependence of the correlation coefficient on the range, depth, and separation of the hydrophones. The data were taken in deep water in the San Diego area. The projector was at a depth of 16 feet and signal lengths of 50 to 100 milliseconds were generally used.

Early work[3] was performed under a variety of refraction conditions at ranges of from 250 to 1750 yards. The two hydrophones were separated either horizontally or vertically, the horizontal separations ranging from 5 to 15 feet. In the vertical separations one hydrophone was always at 16 feet with the other at depths of from 30 to 300 feet. In the later work[13] the experiments were made with a surface-heated layer 10 feet thick overlying an isothermal layer 80 feet deep. The sea state was 1 and the swell from 2 to 3 feet. In these experiments the hydrophones were separated by 2, 5, 10, and 20 feet and were at depths of 16, 24, and 40 feet. Data were taken at ranges from 500 to 1300 yards.

The results of these studies are as follows:

(1) In the earlier, less well-controlled experiments, the correlation coefficient varied from 0.27 to 0.72, the average being 0.45. In the later work it varied from 0.21 to 0.95, the average being 0.75. The latter result is not incompatible with a nearly perfect correlation, since a random experimental error of standard deviation 1.5 db would reduce a perfect correlation to 0.75, the value found. The difference in the average values for the earlier and later work may be due to the inclusion of vertical separations in the earlier work, for which the correlation is less, or to better experimental control in the later work; probably both factors are involved.

(2) There is some indication that the correlation coefficient decreases with increasing vertical separation. The coefficient usually remained significantly positive,

[13] Sonar Data Division, *Correlation of 24 KC Signals Received Simultaneously on Two Hydrophones* (UCDWR M429, July 1, 1946).

however, at vertical separations of almost 300 feet. With one hydrophone at 16 feet and the other at 300 feet, the correlation was 0.34 at a range of 950 yards and 0.38 at 1750 yards.

(3) There is slight evidence that the correlation decreases with range, but this evidence is far from conclusive.

(4) With two hydrophones at one depth there is no dependence of the correlation or either horizontal separation or depth of the two hydrophones.

(5) A comparison of the correlation coefficients and the standard deviations of the signals (i.e., the fluctuation) show a weak correlation between the two, the coefficient being 0.44. A similar comparison of the correlation coefficients and the transmission anomalies showed no significant correlation, the coefficient being −0.1. Thus the agreement between the signals received simultaneously on two hydrophones appears to be independent of the transmission loss but to depend slightly on the fluctuation in the transmission, the agreement being better when the fluctuation is large.

Simultaneous Transmission at Two Frequencies

The correlation between received signals at two frequencies has been investigated by UCDWR.[14] A total of 28 runs was made on four days in deep water under various thermal conditions. On each run signals were transmitted from a single projector at two frequencies and received simultaneously on the same hydrophones. Frequency pairs used were 16-24 kc (or 14-24 kc), and 24-60 kc (or 24-56 kc); hydrophone depths varied from 16 to 300 feet.

[14] Echo-Ranging Section, *Correlation of Simultaneous Transmission in Deep Water at Different Frequencies* (UCDWR A44, October 28, 1944).

Sets of amplitudes were read at various ranges from 160 to 6300 yards, usually from 200 to 2000 yards. The following quantities were calculated:

A. Correlation coefficient between signals received simultaneously at two frequencies.

B. Standard deviation of signals at each frequency.

C. Correlation coefficient between the standard deviations.

The following results were obtained:

(1) The average correlation coefficient of the amplitude fluctuation of simultaneous signals is about 0.3, both 16-24 kc and for 24-60 kc.

(2) These correlation coefficients varied from −0.37 to +0.75; about 60 percent lie between 0.2 and 0.6. There appears no significant dependence on frequency-pair, range, or hydrophone depth.

(3) The average standard deviations for the received amplitudes show no significant dependence on frequency, being about 38 percent for the 16- to 24-kc data and about 47 percent for the 24- to 60-kc data. The difference in the means may be due to differences in the directivities of the projectors used at the two pairs of frequencies, but this is not certain.

(4) The correlation coefficient of the standard deviations is about 0.67 both for the 16- to 24-kc data and for the 24- to 60-kc data. This correlation is strong enough to show that a significant part of the fluctuation at each frequency is due to a common cause. The weaker correlation for the individual amplitudes shows that the source of fluctuation, whatever it may be, does not produce a linear relation of amplitudes at different frequencies.

Standard Deviation of Frequency Modulated Signals

The fluctuation of f-m signals has been investigated by UCDWR,[3] using transmission data recorded on one day in water from 30 to 150 feet deep. The signals were modulated linearly from 24.5 kc to 23.5 kc in 10- and 50-millisecond intervals and were received and recorded by the same systems as those used for the unmodulated signals. Standard deviations were computed at ranges of 300 and 1500 yards for both sweep intervals. The following results were found:

> The fluctuation shows no dependence on recording channel, sweep interval, or range. The standard deviation of the amplitudes varied from 17 percent to 47 percent, the mean value being 35 percent. The standard deviation of unmodulated 24-kc signals of 50-millisecond duration, recorded on the same day at 300 and 1500 yards, varied from 32 percent to 67.5 percent with a mean of 50 percent. Because of the variability of the standard deviation, the difference between the mean deviations for the modulated and unmodulated signals may not be significant.

Fluctuation at Other Frequencies

There is not a great deal of information available regarding the fluctuation of sound transmitted at frequencies different from 24 kc. Some comparative studies were discussed earlier in this report, and the qualitative features of fluctuation at the sonic frequencies described. This latter work was carried out by UCDWR at frequencies of 0.2, 1.8, 7.5, and 22.5 kc.[2] As a rough check on the magnitude of the fluctuation, estimates were made of the quartile deviation of signal amplitudes received at ranges of from 1500 to 3000 yards. Since the data include the 22.5-kc signals, it is possible to compare the results with those for 24 kc. It was found that there appeared to be a slight increase in the magnitude of the fluctuation with frequency, both in deep and in shallow water. The effect is small, however, and may not be real. Moreover, it is probable that the low frequency fluctuation in deep water is range dependent because of the surface image effect, so that such an over-all comparison of the fluctuation at different frequencies without regard to range is not very useful. The data were also analyzed for a dependence on hydrophone depth and refraction pattern. No dependence on either of these factors was found, but again, if the fluctuation depends on the image effect, these factors may be important. This can be decided only by a more detailed analysis.

At the higher frequencies there is some data available from the studies of simultaneous transmission [illegible] frequencies. This work shows that the [illegible] of the fluctuation has no significant dep[illegible] frequency from 16 to 60 kc. In addition [illegible] is a small amount of data taken at 10 kc[5] which indicates a similar result.

Finally there is some data taken by UCDWR during the work on Harbor Surveys.[15] The projector was driven through an overloaded amplifier, with the result that the signal included a large number of discrete frequencies. The output of the receiving hydrophone was fed through four fairly sharp filters in parallel, which were centered at frequencies of 0.6, 2, 8, and 20 kc. These bands were recorded separately by four sound level recorders. Qualitatively, these records show fairly consistently an increase in the magnitude of the fluctuation with increasing frequency. No quantitative analysis of the data was attempted.

The results of this section may be summarized as follows:

(1) There appears to be no dependence of the magnitude of fluctuation on frequency from 10 to 60 kc.

[15] See reference 17, page 102.

(2) From 0.2 to 10 kc there appears to be a slight increase in the magnitude of the fluctuation in both deep and shallow water.

(3) It is probable that at the lower frequencies the fluctuation depends to some extent on the image effect and, therefore, indirectly on the projector and hydrophone depths and range.

Summary of Experimental Results

Before turning to the theories of fluctuation and the discussion of the causes of fluctuation, we shall summarize the main experimental results. It is to be stressed again that some of the results are based on a small amount of data, or represent slight statistical differences, and may not be real.

Rate of Fluctuation at 24 kc

(1) In the direct sound field in deep water the envelope of the received signals is smooth, with amplitude changes taking place in the course of several seconds. The rate of this fluctuation decreases by a factor of three, as the range increases from 100 yards to 1000 yards.

(2) Within the shadow zone or in shallow water with bottom-reflected sound present, the signals resemble reverberation. The envelope is jagged, rapid fluctuations occurring within about 1/10 second and there is a great deal of distortion, i.e., amplitude changes within about 1/100 second. The signals are longer than the transmitted pulse and exhibit "tails."

Distortion of 24-kc Signals

Distortion is most pronounced in the silent "shadow zone" produced when sharp temperature gradients at the surface bend the sound beam downward. In the direct sound field distortion is not usually present.

Magnitude of Fluctuation at 24 kc

(1) The magnitude of fluctuation (standard deviation of the amplitudes expressed in percent of the mean amplitude) varies from 20 percent to 70 percent, the average being 42 percent with quartile deviations of 7½ percent. The distribution of signal amplitudes sometimes fits a Rayleigh distribution or a Gaussian distribution but often fits neither.

(2) The magnitude of fluctuation in the direct sound field shows no strong dependence on thermal conditions, although there may be a tendency for the fluctuation to be larger under good transmission conditions.

(3) With the projector at a depth of 16 feet the average magnitude of fluctuation shows no dependence on range from 100 to 8000 yards, on hydrophone depth from 16 to 400 feet, or on signal length from 10 to 100 milliseconds.

(4) With projector and hydrophone at 16 feet the fluctuation of the direct signal increases slowly from negligible values (1 percent) at a range of 5 yards to 7 percent at 40 yards, where the surface-reflected sound begins to become appreciable. Between 40 and 100 yards the fluctuation of the composite signal increases rapidly to about 40 percent and remains constant thereafter.

(5) With hydrophone and projector at the same depth (150 to 1000 feet) the fluctuation of the direct signal alone is independent of transducer depth and increases as the square root of the range from 6 percent at 40 yards to 50 percent at 3000 yards.

(6) The fluctuation of the surface-reflected signals does not depend on range from 100 to 3000 yards, the average value being 48 percent.

(7) The fluctuation at short ranges (150 yards) is affected by the roll of the sending ship when the roll is more than 4 degrees. The fluctuation is larger when the projector is tilted up toward the surface than when it is tilted down.

Coherence of Fluctuation at 24 kc

(1) The auto-correlation may drop monotonically to zero or may oscillate. In some cases these oscillations appear to be too large to be due to statistical fluctuation, sampling errors, etc., and may be caused by pitch and

roll of the sending vessel. The time scale of the correlation coefficient expands with increasing range, corresponding to the slower fluctuation at long ranges, which is also qualitatively apparent in the oscillograms. In the shadow zone the graphs have the same general appearance as those in the direct sound field, but the time scale is somewhat contracted, in agreement with the reverberation-like character of the shadow-zone signals.

(2) The correlation between the signals received simultaneously on two adjacent hydrophones at the same range and depth is usually high (0.75 percent). It shows no dependence on either hydrophone separation (2 to 20 feet) or hydrophone depth (16 to 40 feet). When one hydrophone is at 16 feet and the other at various depths (30 to 300 feet) the correlation is less (45 percent) and decreases slightly with vertical separation, although it is still significantly positive for separations of nearly 300 feet. In both cases the correlation decreases slightly with range (250 to 1750 yards). The correlation appears to be independent of the transmission loss but to depend slightly on the fluctuation, being higher when the fluctuation is large.

(3) The fluctuation of f-m signals (23.5 to 24.5 kc, linear sweep) in shallow water may be slightly less than for unmodulated 24-kc pings under the same conditions. The fluctuation is independent of range (300 to 1500 yards) and sweep interval (10 to 50 milliseconds).

Fluctuation at Other Frequencies

(1) The rate of fluctuation at 10 kc and 60 kc shows no significant difference from that at 24 kc.

(2) At sonic frequencies (0.2 to 7.5 kc) the rapidity of fluctuation in the direct sound field increases with frequency at short ranges and usually decreases with frequency at long ranges.

(3) Within the shadow zone the signals at all frequencies show a reverberation-like character, with a slow fluctuation of the envelope and a rapid fluctuation (distortion) of the amplitude, the rate of both increasing with frequency. In shallow water the rate of fluctuation increases with frequency at all ranges, the effect being greater at long ranges.

(4) The magnitude of fluctuation is independent of frequency from 10 kc to 60 kc. From 0.2 kc to 7.5 kc there appears to be a slight increase in the magnitude of fluctuation, both in deep and in shallow water. There is evidence that at the low frequencies the magnitude of the fluctuation is related to the image effect pattern and therefore depends on the hydrophone position. Such a dependence at the high frequencies has been observed only at short ranges and with a very calm sea.

Observations on Thermal Structure

Since the velocity of sound in the sea usually depends predominantly on the temperature, it is of interest to consider the thermal structure of the ocean. As a first approximation it was assumed in early work that the temperature of the ocean was constant. While this assumption is useful under certain conditions, it was soon found that the transmission of sound could only be explained by considering the effects of refraction caused by vertical temperature changes. Accordingly, as a second approximation, the sea was assumed to be stratified in horizontal static layers as regards temperature. In a given experiment this structure was determined by the bathythermograph down to 400 feet and a ray diagram was then calculated. This simple model was in general semiquantitative agreement with the major features of the average transmission and proved a useful aid in analysis and in planning research. Except in rare cases, however, it was inadequate to account for the variation in the transmission, and naturally gave no account of the fluctuation in transmission. In order to understand the transmission quantitatively, it is necessary to turn a more realistic model of the thermal structure which includes both large- and small-

scale space changes in the temperature, and also their variation with time. There is insufficient evidence at present to indicate how detailed this model should be or how successfully it could be used to predict the transmission. In this section we shall summarize the small amount of data regarding the thermal microstructure which may be of importance in explaining fluctuation. Results bearing on the slow, large-scale changes which affect the variation of the transmission are given in Reference 1.

Holter Data

Measurements of the thermal microstructure were made by N. J. Holter[16] off the Pacific Coast. Thermopiles were attached to the keel of a surface vessel. Later, to eliminate pitch and roll, they were attached to a submarine. In both types of experiments the recorded temperature differences represent both time- and space-changes which cannot be separated. A serious additional defect in the use of the surface vessel is the large pitch and roll which moves the thermopile vertically through the existing gradients and gives a spurious temperature fluctuation. In the submarine experiments this effect, while not absent, is much smaller and more reliable measurements are obtained.

In a typical experiment the submarine traveled submerged at a speed of 100 yards per minute (3 knots) with the thermopile at a depth of 64 feet. The temperature was recorded as a function of time (or horizontal distance). The record shows variations as large as 0.2 degree F (1 ft./sec. in sound velocity) over a distance of 20 to 30 yards (15 to 20 seconds), such changes occurring several hundred yards apart. Between these large horizontal gradients the temperature varies rapidly by steps of the order of 0.01 degree F. Holter sums up the results on the horizontal thermal structure as existing on at least three different scales:

(a) Large scale changes, occurring in distances of the order of 200 yards, with temperature differences of 0.5 degree F.
(b) Medium scale changes, occurring in distances of the order of 50 yards, with differences of 0.1 degree F.
(c) Microstructure distances of the order of 10 yards, with differences of 0.02 degree F.

Holter has pointed out[17] that the slow response of the equipment used would have prevented the recording of irregularities having dimensions less than 10 yards (duration less than 6 seconds at a submarine speed of 6 knots). The possible existence of such very short term irregularities is therefore unsettled.

In another experiment Holter measured the variability of the vertical gradient by means of two thermopiles mounted at depths of 58 and 64 feet and connected so that the difference of their respective voltages (and therefore difference in their temperatures) was recorded. In some cases the vertical gradient changes by as much as 0.01 degree F per foot depth over a horizontal distance of 100 yards (1 minute at 3 knots), and 0.05 degree F per foot over 20 yards (12 seconds). At other times the record is much smoother, with the variation remaining less than 0.01 degree F per foot depth over a distance of 1000 yards (10 minutes).

Urick Data

R. J. Urick[18] has observed the vertical microstructure of the temperature by means of an acoustic interferometer lowered from a surface

[16] N. J. Holter, *Measurements of the Horizontal Thermal Structure of the Ocean* (U.S.N. Radio and Sound Laboratory Report S-17, August 18, 1944).

[17] Sonar Analysis Section, *Fluctuation of Transmitted Sound in the Ocean* (CUDWR, Tech. Memo. No. 6, December 22, 1944).

[18] R. J. Urick, *An Acoustic Interferometer for the Measurement of Sound Velocity in the Ocean* (U.S.N. Radio and Sound Laboratory Report S-18, September 18, 1944).

vessel. General agreement was found with the gross temperature gradient recorded simultaneously by a bathythermograph, but in addition a fine-scale structure was found. These irregularities were of the order of 0.2 degree F (1 foot/sec. in sound velocity) and extended over a region of the order of 1 foot. This structure was not stationary since a different structure was observed when the instrument was lowered than when it was raised. Unfortunately, this evidence is difficult to evaluate since it is open to the same defect as Holter's surface-ship data, namely, the pitch and roll of the ship moved the measuring device through the thermal gradients to produce a spurious microstructure.

4. CAUSES OF FLUCTUATION: DISCUSSION AND CONCLUSIONS

At the present time there exists no general theory of the fluctuations of sound in the sea. One reason for this lies in the fact that the subject is extremely complex; indeed, not even the average transmission of sound in the sea is understood as yet in any but a qualitative and empirical way, and a clear understanding of this is a prerequisite to the understanding of the fluctuation. Second, very few empirical conclusions have been reached, although there is a great amount of data on transmission which should yield valuable information if and when it is analyzed. Thus, there is virtually no evidence on fluctuation at frequencies other than 24 kc, nor on the important features of either the surface of the sea or its thermal structure. Finally, there has been only a relatively small amount of theoretical work on fluctuation; as will be seen below, the investigations are analyses of only one or two of the various mechanisms which are probably important in fluctuation. Nevertheless, in spite of the small amount of data and theory it is possible to reach some conclusions which should be helpful in forming a rough qualitative picture of fluctuation and in guiding future research.

On page 104 we shall discuss the causes of the very rapid type of amplitude change which has been called distortion.

On page 105 we shall summarize the various theories of fluctuation and compare them with the experimental results. Before doing this, however, three remarks are in order:

(a) It will be seen that many of the mechanisms are highly idealized and quite obviously do not apply to fluctuation at 24 kc (e.g., image effect with a mirror surface); nevertheless, they will be discussed because they represent a first approximation and because of their probable importance at the lower frequencies.

(b) There is no single mechanism or cause of fluctuation, although this impression may be gained from some of the theoretical discussions. Instead, it is probable that there are a number of mechanisms which contribute to the fluctuation, their relative importance depending on all of the various factors involved. Thus, under rare circumstances, the fluctuation at 24 kc may be nearly explained by a simple modification of the image effect (cf. Fig. 12), while under usual conditions a much more involved theory of surface reflection is required.

(c) In deciding between the various theories on the basis of experimental evidence, it is often necessary to compare the predicted distribution of signal amplitudes with the observed distribution. In doing this it should be remembered that the various theoretical distributions often differ only in the form of their "tails," i.e., in the distribution of, say, the highest 5 percent of the amplitudes, as shown in Figs. 13, 14, and 15. A general agreement between most of the data and a theoretical distribution

curve is therefore not a very significant check of a theory; what is required is a good fit in the region of the tail also, and this of course requires a large amount of data.

Causes of Distortion

As has already been remarked, in those cases where the ray theory predicts a silent shadow zone near the sea surface, the distortion in deep water is most pronounced at long ranges, where the transmission loss is high. At 24 kc, the explanation of this phenomenon is believed to be scattering from suspended obstacles in the water, especially those forming the deep scattering layer.[19] This is suggested by the fact that the distorted signals are very similar in appearance in reverberation, which is known to be caused by scattering, and is in quantitative agreement with observation in certain cases recorded in earlier references.

Figure 20 shows schematically how forward scattering can explain the short pulse observed at long ranges.[19] The explanation depends on the fact that the path difference, via the various scatterers, are small, so that all the scattered sound reaches the hydrophone at nearly the same time. With the hydrophone at shorter ranges the path differences are larger and the scattered sound is received over a longer period. This "smears" out the pulse and explains the presence of the "tail."

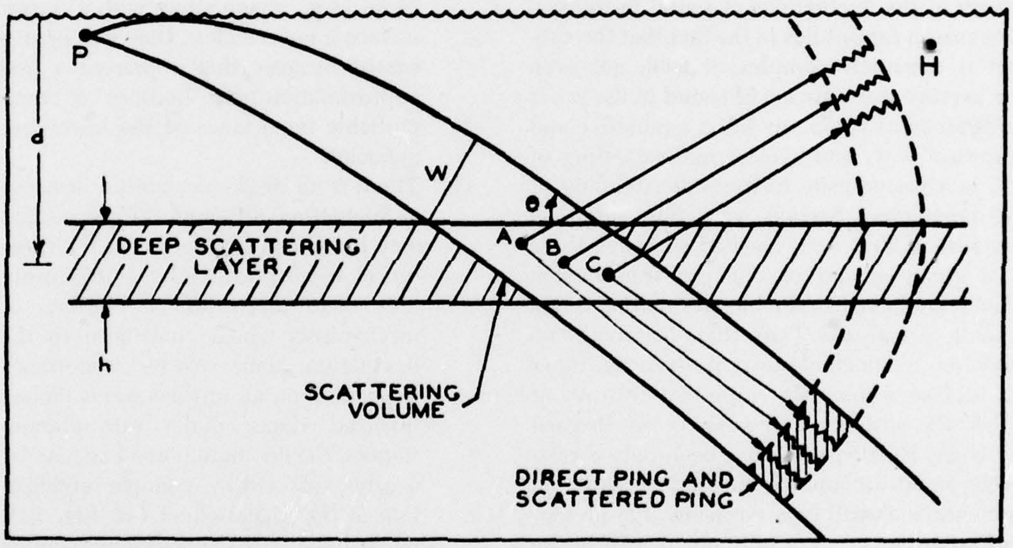

FIG. 20. Forward scattering from the ECR layer.

The level of the scattered sound which this mechanism predicts depends on the projector output, the beam pattern, the scattering coefficient and thickness of the deep layer and the refraction conditions. This theory has been checked quantitatively in a few cases where vertical beam measurements were made in conjunction with transmission runs.[19]

It therefore appears that scattering from volume scatterers is responsible for the reverberation-like signal obtained at 24 kc in the

[19] Sonar Data Division, *Forward Scattering from the Deep Scattering Layer* (UCDWR M398, March 19, 1946).

shadow zone, and interference of the scattered waves is the cause of the accompanying rapid changes in the amplitude which we have called distortion.

It is equally clear that scattering cannot be a significant cause of fluctuation of the signals in the direct sound field, since the intensity of the scattered sound is 40 or 50 db below that of the direct sound. Thus, while scattered sound is present in the direct sound field (indeed, it is observed near the projector as volume reverberation), it is far too weak to influence the transmission and cause fluctuation.

It may be mentioned here that with a deep isothermal layer above a negative gradient there is a transmission loss as the sound goes through the thermocline. The intensity below the layer is therefore less than the intensity above the layer. At long ranges and with sharp thermoclines, this loss may result in a weak shadow below the layer, and it would be expected that the scattered sound might predominate here, just as it does in the shadow produced by downward refraction. This has in fact been observed; the strong direct and surface-reflected signals have been recorded above the layer, while below the layer the signal has the distorted reverberation-like character expected of scattered sound.

In shallow water the distortion of the signals is probably caused by the interference of the direct sound with multiple surface and bottom reflections.

Causes of Fluctuation

The following discussion leans heavily on References 17, 26 and 27.

Relative Motion of Projector and Hydrophone

No general analysis of the effect of relative motion of projector and hydrophone on fluctuation is available, nor is there sufficient data to warrant an empirical study. The effects are undoubtedly present in the 24-kc transmission data, however, and a brief and simplified discussion will be useful. The motion may be broken down into three components: (1) relative horizontal motion, (2) relative vertical motion, and (3) relative rotational motion. The first two motions can cause fluctuation because the hydrophone will move through the spatial image effect pattern due to the projector; this can arise even with non-directional transducers. The third motion will be caused by pitch and roll of the sending and receiving vessels to which the transducers may be rigidly attached.

A rare example of the fluctuation observed at high frequencies and short ranges is shown in the 20-kc record of Fig. 12 which has already been discussed. In addition to the regular fluctuations caused by the maxima and minima of the interference pattern, there is a great deal of irregular fluctuation, presumably owing to small irregular motions of the projector, hydrophone, and surface. We shall first see whether forward motion of the ship through the maxima and minima can explain the observed fluctuation at 24 kc at long ranges; we shall then consider the irregular type of fluctuation.

Forward Motion of the Sending Ship

For simplicity we shall assume the projector and the hydrophone to be non-directional and the surface to be a perfectly reflecting flat mirror. We wish to examine the fluctuation due to the forward motion of the source, or, what is the same thing, the fluctuation resulting from the horizontal motion of the hydrophone through the stationary spatial interference pattern due to a fixed source at a depth of 16 feet which is emitting 24-kc sound. This pattern is shown in Fig. 21 and will now be explained. The image effect intensity is given by

$$I = 4I_1 \sin^2(\pi d/\lambda),$$

where

$$I_1 = I_0/R^2$$

is the intensity of the direct sound alone (in-

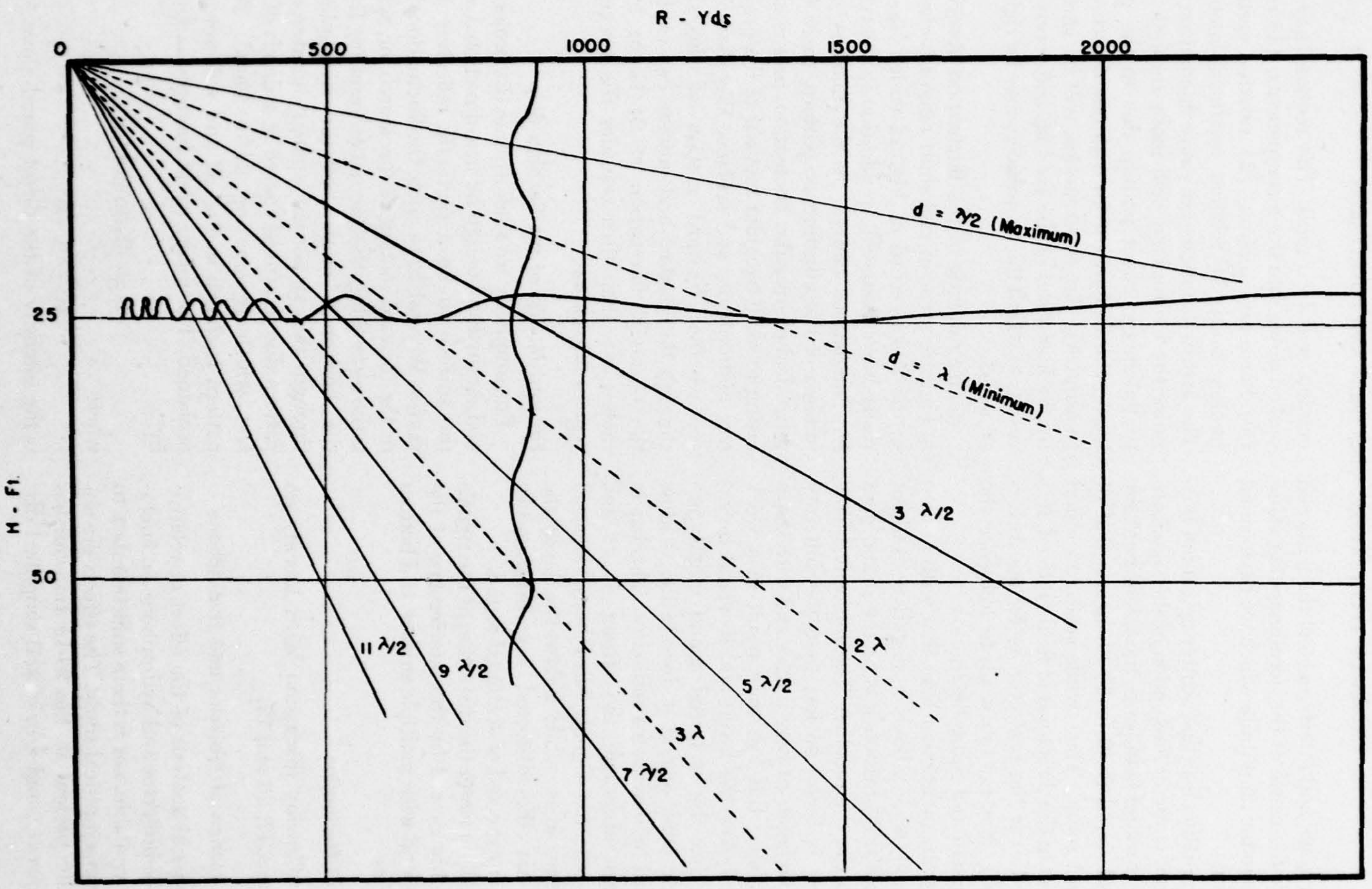

FIG. 21. Image interference.

verse square law), I_0 being the source intensity at unit distance and R the range. The quantity

$$d - 2ph/R$$

is the path difference between the direct and surface-reflected rays, p and h being the projector and hydrophone depths and λ the wave-length of the sound (1/5 foot at 24 kc). Neglecting the inverse square effect, which is a steady decrease, and considering only the $\sin^2$ term, it is seen that the intensity is a maximum along the lines shown for which $d = \lambda/2$, $3\lambda/2$, $5\lambda/2$, etc., and drops to zero between these lines. Thus, a hydrophone moving horizontally at the 25-foot level will record a maximum whenever it crosses one of these lines, as shown by the varying intensity curve. A similar variation will be found if the hydrophone is moved along a vertical line, say at a range of 650 yards.

At a range of 115 yards with hydrophone depth 25 feet (Fig. 21) the path difference is 11 wave-lengths and the maxima are about 10 yards apart, corresponding to 7 seconds or 14 signal intervals at 2.5 knots, the mean speed during the experiments where results are shown on Fig. 16 A. Clearly the observed fluctuations are about ten times more rapid than the regular interference maxima attributable to the forward motion of the sending vessel.

At a range of 965 yards (Fig. 16C) the pattern will be somewhat distorted by refraction[10] but the shift in maxima is not large and we may use the constant velocity pattern shown in Fig. 21 as a rough approximation. It is seen that the observed fluctuations at this range also are far too rapid to be attributable to the forward motion of the projector.

Thus it appears that the fluctuation due to the forward motion of the projector is far too slow to explain the observed fluctuation at 24 kc. This result is hardly surprising; the non-specular character and known large fluctuation of the surface-reflected sound make it evident that the present simple model is very unrealistic at the high frequencies.

Vertical Motions of Projector, Hydrophone, and Surface

In addition to the regular fluctuation which is caused by the horizontal motion of the projector or hydrophone, there will also be present a fluctuation due to the roll and pitch of the sending vessel, the variable height of the surface, and the unknown motions of the hydrophone at the end of its cable. These various effects are only partially regular, since their periods and amplitudes vary. Their net effect may therefore be expected to be somewhat irregular. If these many irregular fluctuations are large enough, they may be dominant.

In Fig. 21 it is seen that the vertical intensity pattern is relatively fine-grained at 115 yards, so that relative motions of projector, hydrophone, and surface of only 1 or 2 feet would be sufficient to cause the fluctuations shown in Fig. 16A. At 965 yards it is seen that the vertical pattern is more coarse-grained, so that vertical motions of the order of 5 to 10 feet are required to explain the fluctuation shown in Fig. 16C. The maximum height of the swell was about 3 to 4 feet and the vertical motion of the hydrophone due to roll of the receiving vessel was about the same order of magnitude. This amount of motion is therefore large enough to explain Fig. 16C.

Pitch and Roll of the Sending Ship

Even in calm weather both transmitting and receiving ship are subject to roll and pitch (as well as yaw, which we ignore), with the result that the bearing of the projector and receiver relative to each other and to the surface (and bottom) of the sea are not constant. With non-directional transducer this would, of course, produce no change in the transmission, but with highly directional units these motions may cause fluctuation.

First, consider the direct sound field alone

and suppose the hydrophone to be rigidly mounted and the projector to rotate so that the horizontal angle of the sound beam varies periodically. This constitutes a simple model of a transmitting ship which is rolling and pitching. As the sound beam sweeps up and down over the hydrophone it will produce fluctuations in the received sound with a period equal to that of the roll of the sending vessel.

Now consider the surface-reflected sound. It may be regarded as coming from an image source above the surface. This image source will be oscillating with the same period as the true source, but the hydrophone will be at a different relative angle of dip. Hence the relative amplitudes of the direct and surface-reflected sound will vary and produce a fluctuating interference pattern at the hydrophone. If the two rays are out of phase by 180 degrees, the resultant change in the intensity distribution of the interference pattern may become very appreciable, even with comparatively minor changes in the relative intensity of the two rays. These effects may be complicated still more by refraction and by the roughness and motion of the surface. The latter apparently causes the surface-reflected sound to have a larger fluctuation than the direct sound. Since the magnitude of the fluctuation of the direct sound increases with range, it will be seen that the problem of predicting the fluctuation of the signal from the known roll and pitch may be very difficult indeed. In particular, it is by no means evident that the rapidity of the observed fluctuation due to roll and pitch will be independent of the range. This would be the case only if there were no interference effects and the changes were due entirely to the beam pattern.

The chief argument in favor of roll and pitch as a direct cause of signal fluctuation at 24 kc is the occasional presence of a periodic character in the fluctuation, as shown by the autocorrelation graphs. This period is of the order of the known period of pitch of the sending ship in many of the UCDWR experiments.

On the other hand, it has been found that the rate of the rapid fluctuation in the direct sound field decreases with range and this has been used as an argument against the hypothesis that roll in an important cause. It will be clear that the facts are not simple, and that care must be exercised in drawing conclusions.

About all that can be concluded is that roll and pitch cannot be the main cause of fluctuation but rather that it slowly modulates the rapid fluctuation already present.

Interference Between One Direct and a Few Surface-Reflected Rays

The analysis of the irregular fluctuation is a statistical problem. If the received signal is the resultant of two sources of equal intensity (one being the direct source; the other being the surface image) with random phase difference, then the probability that the measured amplitude will exceed a pre-assigned value a is

$$P = (2/\pi)\ \cos^{-1}(a/2a_0),$$

where a_0 is the amplitude due to either of the two sources alone. Note that a cannot exceed $2a_0$ and that the probability that $a = 2a_0$ is zero. Equation (3) leads to the following values of the mean amplitude a and the standard deviation σ:

$$\bar{a} = 4a_0/\pi = 1.28\ a_0,$$
$$\sigma = 0.483\ \bar{a}.$$

Expressed in terms of the mean amplitude, P becomes

$$P = (2/\pi/)\ \cos^{-1}(2a/\pi\bar{a})$$

and can be compared with the observed distributions. This function is completely inadequate as a representation of the data on Figs. 14, 15, and 16, since many of the observed amplitudes exceed $2a_0$, i.e., for which $(a/\bar{a})^2 > (\pi/2)^2 = 2.47$.

A similar result is obtained if it is assumed

that the surface reflected ray has a constant amplitude μa_0 different from the direct amplitude, μ being the surface reflection coefficient ($\mu \leq 1$).

Both of these assumptions are thus contrary to experiment for high frequencies. They may be good approximations for explaining the fluctuation at low frequencies.

These calculations can be extended to the case of a small number of rays of equal (or even unequal) amplitude. The basic formulae are to be found in Whittaker and Robinson, § 85. Numerical tables facilitating the calculations have been published, and applied to the present problem by Schiff and by Hebb and Blachman.[20] As the number, N, of equal interfering components increases from 2 to 7, the ratio $\sigma / \bar{a}$ increases from 0.48 to 0.51. As N approaches infinity, the Rayleigh distribution (see section on "Distribution of signal amplitudes") is approached, with $\sigma/\bar{a} = 0.52$. For $N > 4$, it would require an excessively large amount of data to determine its value from the empirical distribution curve, as there is very little difference between any of the curves for $N > 4$ and for $N = \infty$.

Reflection of Sound from a Rough Surface

Since the sea surface is clearly not a plane, the image of a source reflected in the surface will be greatly distorted. Since the surface is also in motion, the distortion, as well as the position and intensity of the image will change from moment to moment. At high frequencies this image will very likely correspond more nearly to the scintillating "sunpath" which makes sunset at sea so spectacular, than to the image in a mirror. Thus the surface-reflected sound may be considered to come from multiple "dancing" sources of varying intensity. Nor is the intensity of the direct sound constant; it also fluctuates, so that the source, as "seen" by the hydrophone via direct rays, probably "twinkles" like a star seen through the earth's atmosphere.

The resultant of these two variable sounds, the direct and the surface-reflected, is the observed signal, and the analysis of its fluctuation must include the fluctuation in each component. As a first approximation the problem may be simplified in two ways:

(1) The direct sound may be considered approximately constant so that the fluctuation in the signal is due entirely to the surface-reflected sound. This is justified by the observed small (20 percent) fluctuation of the direct sound at short ranges (200 to 500 yards).

(2) The surface may be considered as "frozen" for the duration of a short ping, so that time changes occurring within, *say, 50 milliseconds*, can be ignored. This simplification is suggested by the observations that the surface is essentially motionless for periods of the order of 30 milliseconds.

Thus simplified, the problem is to describe the fluctuation from ping to ping in the intensity of the sound reflected from a rough surface whose form is constant during the ping but changes from one ping to the next.

Sometimes (see below) the problem has been further simplified by considering the irregularities of the surface to be spaced periodically; this is not justified, since such a surface concentrates the reflected energy into a very few beams that come from regularly spaced, and very slightly distorted images. The essentials of the problem are presumably lost in this idealization.

The case most appropriate to reflection at 24 kc is probably that where the surface is irregular and the size of the irregularities is of the order of magnitude of the wave-length. The parameter of size turns out to be the projection of the surface wave amplitude onto the oncoming wave front. Thus, for surface waves of

[20] M. H. Hebb and N. M. Blachman, *Variation of Signal Amplitude after Transmission in the Sea* (HUSL Memo., December 19, 1944).

height 2 feet, and for a grazing angle of 6 degrees, the projected wave height is 1/5 foot, which is just equal to the wave-length of 24-kc sound. It will be appreciated that this is precisely the intermediate case most difficult to treat theoretically.

Historically the subject was treated by Rayleigh[21] (Vol. II) for the case of normal incidence on a surface having periodic corrugations large compared to a wave-length. Ornstein[22] treats the case where the surface is composed of randomly oriented plane mirrors large compared to a wave-length. It is possible that the Rayleigh case, using grazing incidence, might be appropriate to high frequency sound reflected from a sea surface which is smooth but which has a swell. The Ornstein case may fit the reflection of very high frequency sound from a rough sea surface, swell being absent, although the mirrors should be curved if the model is to be realistic. This is essentially the theory treated by Eckart (see below).

(a) *Schiff's calculation.*—In a series of memoranda,[23-25] Schiff has treated the problem of reflection of acoustic waves from surfaces which differ only slightly from surfaces for which a rigorous solution of the wave equation is known. This approach follows that of a paper by Feshbach and Clogston[26] in which this problem has been reduced to the solution of an integral equation, but goes beyond it in so far as Schiff treats cases which have a continuous spectrum of characteristic values. Certain major theoretical questions remain to be studied, however.

(b) *Bergmann's calculation*[27].—This calculation is based on the same approximation as Schiff's, but is restricted to the case of small glancing angles and/or small wave height (see above). Under these conditions, Bergmann's calculation supports Schiff's, in that both predict specular reflection as well as diffuse scattering.

(c) *Eckart's calculation*[28].—This is based on geometric optics, and is therefore valid only when the wave-length of the sound is very much less than the mean size of the surface waves. To a certain extent, this is the limiting case opposite to that treated above. The sea surface is treated by a combination of the methods of statistical theory and differential geometry. In order to evaluate the necessary integrals, the slope of the sea-surface must be considerably less than one radian. The conclusion is that under these circumstances, a single point source has many images, whose number and intensity can be treated statistically.[29] The sea surface is shown to be specifiable by a system of nine parameters, all of which enter into the final formulae.

Interference between Rays Sent by Thermal Structure

The fact that the observed signal amplitudes sometimes fit the Rayleigh distribution curve has led to the consideration of the interference of a number of direct rays having equal amplitudes and random phases. While such a mechanism would result in a Rayleigh distribution, it is unsatisfactory as an explanation for the

[21] Lord Rayleigh, *The Theory of Sound* (London, 1894), second edition.

[22] L. S. Ornstein and A. Van Der Burn, "Reflectivity of corrugated surfaces," Physica 4, 1181 (1937).

[23] L. I. Schiff, *Preliminary Report on the Solution of the Acoustic Boundary Problems* (University of Pennsylvania, September 4, 1943).

[24] L. I. Schiff, *Solution of Acoustic Boundary Problems II* (University of Pennsylvania, October 7, 1943).

[25] L. I. Schiff, *Solution of Acoustic Boundary Problems III* (University of Pennsylvania, November 2, 1943).

[26] H. Feshbach and A. M. Clogston, "Perturbation of boundary conditions," Phys. Rev. 59, 189 (1941).

[27] P. G. Bergmann, Sonar Analysis Group, *Reflection from Rough Surfaces* (Sonar Analysis Group Tech. Memo. No. 8, November 1, 1946).

[28] Sonar Data Division, *The Sea Surface and Its Effect on the Reflection of Sound and Light* (UCDWR M407, March 20, 1946).

[29] P. G. Bergmann, "Propagation of radiation in a medium with random inhomogeneities," Phys. Rev. 70, 486 (1946).

fluctuation of the observed signals, as pointed out by Bergmann.[17] The most important objection is that the surface reflected sound is neglected; again, the Rayleigh distribution is by no means typical of much of the data; finally, it appears unlikely that the component interfering rays will all have the same amplitude. In addition to these objections, the lengths of the various paths must be at least of the order of one wave-length if the rays are to have random phases, and, as shown below, this appears to be incompatible with the order of magnitude of the microstructure suggested by Holter's measurements.

Nevertheless, the mechanism is of interest in explaining the observed fluctuation of the direct sound alone. Since the distribution function for the direct signal amplitudes is not known, there is no need to impose the requirement that it be Rayleigh, and that the amplitudes of the interfering rays are necessarily equal. Two cases may be considered; the first assumes that the various interfering rays travel from the projector to the hydrophone along nearly equal paths; the second assumes that the paths are quite different.

For the first case, it is assumed that in some way multiple paths are established and the path difference for rays which travel over slightly different paths through the thermal microstructure is calculated. The root mean square deviation of the acoustical path is found to be.[17, 29]

$$S = \sqrt{(cR)}^{1/2} (\triangle v/v),$$

where c is the size of the thermal "patches," R the slant range, $\triangle v$ the deviation of the local "patch" velocity from v, the mean velocity. For example, to use values suggested by Holter's data, if the average size of a patch is assumed to be 20 yards and the amplitude of the temperature microstructure were 10^{-2} degree F., then $\triangle v/v$ would be 10^{-5}, and at a range of 500 yards S would be 10^{-3} yard. Now the wave-length of 24-kc sound is 0.6×10^{-1} yard, so that the r.m.s. deviation in path difference would be only 1/60 of a wave-length. This is much too small to cause a fluctuation of 20 percent in the direct signal, as is observed. For path differences of the order of a wave-length, both the temperature differences and average extension of the thermal patches would appear to have to be about ten times the above values. But even if larger-sized patches are assumed to be the chief cause of fluctuation, the expected difference between path lengths will still be small compared to a wave-length, since two alternative paths would pass through sufficiently closely adjoining regions so that the large patches would not become effective in establishing large differences in path length.

It thus appears unlikely that in its present form this multiple path theory can account for the observed fluctuation in the direct signals. Inasmuch as the temperature data are preliminary, this conclusion is only tentative and may be invalidated by further observations. Also, a modification of the theory, in which different amplitudes are assumed for the various rays, might be considered.

The second case, in which the several interfering rays travel over quite different paths, is well known to exist under certain thermal conditions.[5, 30] This can occur when a layer containing a sharp negative gradient overlies a layer with a weak gradient. If the projector and hydrophone are in the lower layer there will be a nearly straight ray between them. But there will also be a ray which rises into the upper layer and is bent back by the strong gradient so that it crosses the nearly straight ray in the lower layer. A hydrophone placed at the intersection of these two rays will receive direct sound by two separate paths.

This mechanism was clearly demonstrated in the transmission or explosive impulses[30]

[30] T. F. Johnston and R. W. Raitt, *Transmission of Explosive Impulses in the Sea* (UCDWR U8, December 2, 1947).

when two or three distinct direct signals were received. In a typical case the time lag between two such direct signals received at a range of 1110 yards was 0.1 millisecond, corresponding to a path difference of 1 foot or 5 wave-lengths at 24 kc. This is certainly sufficient to cause large fluctuations from signal to signal (unless, of course, the paths are extremely stable so that the path differences from ping to ping remain constant, a situation which almost certainly does not exist).

Unfortunately it is not known how often this mechanism is effective or how well it can account for the observed fluctuation of the direct signal, particularly as regards the increase of the fluctuation with the square root of the range.

Focusing and Defocusing by Thermal Lenses

It has been suggested by Bergmann[17, 29] that the fluctuation of sound in the sea might be caused by the action of large thermal patches which act like lenses and focus or defocus the sound rays passing through them. This lens mechanism is quite different from the interference effect discussed in the previous section. In the interference effect the thermal structure introduced path differences between the various rays and refracted them so that they then interfered at the hydrophone to give a fluctuating signal. In the case of the thermal lenses, on the other hand, the fluctuation is caused by the changing intensity of the sound received over even a single direct path. Bergmann's theoretical analysis leads to the result that the fluctuation caused by thermal lenses should increase as $R^{3/2}$, R being the range. Since the theory is based on ray acoustics, the fluctuation should be independent of frequency as long as the wave-length is small compared to the lenses.

Experimental data bearing on this theory are provided by the observations of the fluctuation in the direct sound. Since these data showed the fluctuation to increase as $R^{1/2}$, they apparently conflict with the theory. In addition, the predicted magnitude of the fluctuation, based on Holter's thermal data, is apparently much smaller than is observed.

Thus Bergmann concludes that the available experimental data disagree with the thermal lens theory of fluctuation of the direct sound. Much more data and a more detailed analysis of the experimental results are needed to afford a conclusive check, however.

Conclusions Regarding Fluctuation at 24 kc

In this section we shall summarize in a general qualitative way the principal conclusions to be drawn from the experimental results on page 100 and the theoretical discussions on pages 104-112. The conclusions will be confined to fluctuation at 24 kc, since there is inadequate evidence, both experimental and theoretical, at the other frequencies.

General Picture

The sound field in deep water may be regarded as the resultant of three components:

(1) direct sound,
(2) surface-reflected sound,
(3) volume-scattered sound.

Volume-scattered sound is important only in the shadow zone where the direct and surface-reflected sound have been removed by strong downward refraction. In the direct sound field the direct and surface-reflected sound are stronger than the volume-scattered sound and they determine the resultant intensity and fluctuation of the received sound. In shallow water a fourth component, bottom-reflected sound is important.

Fluctuation of Direct Sound

The fluctuation of the direct sound increases from a negligible value at short ranges to large values at long ranges; inside 500 yards it is small compared to the fluctuation of the surface-reflected sound. The fluctuation of the direct sound must be attributed to the pres-

ence of inhomogeneities in the volume of the sea. It is believed that thermal inhomogeneities are primarily responsible for the fluctuation, and three mechanisms have been suggested:

(1) *Interference of several refracted rays which travel over quite different paths, phase differences being introduced by the different path lengths.*—This mechanism has been found experimentally. While it could account for the fluctuation, it is not known how often this mechanism is present or whether it could explain the range dependence of the observed fluctuation.

(2) *Interference of several rays which travel over nearly the same path, phase differences being introduced by the thermal structure through which the different rays have passed.*—This mechanism has been studied theoretically, although the theory does not explain how the multiple paths are established. In addition, the various rays are assumed to have the same amplitude. Using preliminary thermal structure data, the theory predicts phase differences which are far too small to account for the observed fluctuation, so that this mechanism is inadequate.

(3) *Focusing and defocusing by thermal lenses.*—In this case the fluctuation is caused by variations in intensity for one ray, rather than interference of several rays. The theory of this mechanism predicts a different range dependence from that observed, and, on the basis of preliminary measurements of thermal structure, predicts a much smaller magnitude of fluctuation than is observed. More careful study of this mechanism, both theoretically and experimentally, is needed before definite conclusions can be reached.

Fluctuation of Surface-Reflected Sound

The fluctuation of the surface-reflected sound is large and independent of range. It is caused predominantly by the roughness and motion of the surface, although some fluctuation must be introduced by the inhomogeneities in the volume of the sea. The theory of reflection of sound from a rough surface may be divided into three cases, according as the scale of the surface roughness is large, of the order of, or smaller than, the wave-length of the sound. It is probable that all three cases will be required to adequately describe the reflection of 24-kc sound from a sea surface which ranges from dead calm to rough and may include swell.

Fluctuation of Resultant Sound

The fluctuation of the resultant signal in the direct sound field is due to the interference of the direct and surface-reflected sound and to the fluctuation inherent in each. The magnitude of the observed fluctuation is large and independent of range. For transducers mounted on surface ships the rate of the observed fluctuation decreases somewhat with range.

If the surface were a mirror and the direct and surface-reflected sound were constant in time and space, their resultant intensity would be given by the image interference pattern. If this pattern is assumed, it is found that:

(1) The fluctuation produced by the horizontal motion of the sending ship is much slower than the observed fluctuation.

(2) The vertical motion of the projector, hydrophone, and surface could account for the observed fluctuation at short ranges but not at long ranges.

In addition to these motions, fluctuation may be caused by the pitch and roll of the sending ship. There is good evidence that this cause is operative in about half the runs which have

been analyzed for fluctuation. The fluctuation due to roll and pitch is relatively slow and modulates the rapid fluctuation always observed at close ranges.

Distortion of the Signals

Rapidly fluctuating, reverberation-like signals are received in the shadow zone. These signals are relatively weak and consist of volume-scattered sound from scatterers located in the volume of the sea. The distortion in these signals is caused by the interference of sound from the various scatterers, just as in volume reverberation.

5. POSSIBLE FUTURE RESEARCH

The Scientific Importance of the Fluctuation Problem

It can be argued that the basic distinction between the methods of laboratory physics and those of geophysics is to be found in their treatment of the phenomena of fluctuation and departures from the average.

The laboratory method consists in controlling the environment of an experiment to such an extent that one factor (or a small group of factors) is quantitatively dominant. Under these conditions, relatively simple mathematical equations to describe the experiment can be set up and verified with striking precision. The departures from these laws are so small that they can either be ignored completely, or dismissed as "experimental error." Only when extreme precision, or a very complex system of measurements is involved, does the problem of fluctuation become embarrassing. When it does arise, the laboratory physicist is as helpless as the geophysicist—vide the lengthy discussion during the 1930's as to the most probable values of the fundamental physical constants.

The geophysicist, in common with all observational scientists, must deal with many, almost equally important factors. Traditionally, the astronomer is an exception to this rule, because he originally confined his attention to those phenomena in which gravitation is the dominant agent. However, the motion of the planets and the tides are rare exceptions among natural phenomena. Measurements of almost all others result in scatter diagrams or wiggly graphs rather than in analytic functions.

Progress in the observational sciences will be slow if this complexity in the observed phenomena is ignored. The methods of measurement must be based on those of the laboratory physicist, and wherever possible, they must be calibrated in the laboratory, and yield "smooth" curves under these conditions. However, there is no reason to apologize if they yield "wiggly" curves in the field. *This is the* essence of the problem, and the methods of analysis should anticipate this outcome of the measurements.

The methods of data analysis and interpretation employed in the laboratory are not adequate in geophysics. These methods have been devised to fit the case when one factor is sufficiently dominant over all others to obscure their effects and when the experiment yields a graph that can be fitted by a simple analytic equation. Even if many equations are taken over from the laboratory, and an attempt is made to dovetail them by means of common sense, the result is not certain to be correct. This is not obvious. The procedure just described is standard in geophysics and sometimes leads to a useful description and interpretation of nature (e.g., the recent work on ocean swell). However, it has been tried in the case of underwater sound and has failed conspicuously. As has been brought out in the previous pages, the variations of transmitted intensity are not explained, but rendered more mysterious, when an attempt is made to ex-

plain them on the basis of one or two simple processes.

There is no reason to believe that the fluctuations of underwater sound are exceptional in their basic complexity. In general, the geophysicist has attempted to follow the lead of the astronomer, and to study first those phenomena in which one factor dominates. If the dominance is even moderate, this theoretical method seems to have a moderate success, particularly if the acceptable experimental error is increased.

On the other hand, fluctuations comparable to those of underwater sound transmission are observed in many fields. A few are:

air and water temperatures,
wind speed and direction,
barometric pressure,
ocean currents,
ocean waves (as distinct from swell),
terrestrial magnetism,
turbulent motion in general,
mixing processes in the ocean and atmosphere.

All of these phenomena result in scatter diagrams and wiggly graphs. It is unlikely that any of them will be explicable by theories that are casually constructed out of bits and pieces borrowed from the laboratory.

Some of the phenomena listed above are of greater scientific and practical importance than underwater sound. Perhaps the scientific importance of studying the fluctuation of the latter is largely derived from the fact that it is typical of so many other geophysical phenomena. Or, possibly, the failure of an accepted scientific method is itself sufficient justification for further work.

Proposed Theoretical Research

Fluctuation and the Mixing Process in the Upper Layers of the Ocean. The theory of fluctuation of underwater sound transmission is obviously very closely related to the theory of the thermal gradients in the ocean. The manner in which these are caused by the combined action of the sun, the wind and surface waves, and the mixing processes, is not quantitatively understood, although fairly satisfactory word theories have been developed. The mixing process is especially closely connected with the unexplained aspects of fluctuation, since it must involve the existence of local gradients. The magnitude and extent of these inhomogeneities in the temperature field is difficult to measure and has never been calculated.

A preliminary theoretical analysis substantiates the above. When the general hydrodynamic equations are set up in such a manner that thermal conductivity and the diffusion of solutes are included in them,[31] the propagation of sound is automatically included also. Thus, *the basic equations for a unified theory of thermal and acoustic phenomena in the sea are already available; it remains to find the appropriate solutions.*

The basic equations are non-linear, so that only approximate solutions can be expected. The decision as to the proper approximations to make can only be based on a systematic dimensional analysis of the problem, inclusive of empirical data as to the order of magnitude of some of the phenomena. When this has been done, the mathematical work will be reduced to the successive solution of the zeroth, first, second, . . . order equations. Many of the solutions of the zero- and first-order equations are well-known and are the "laboratory" solutions mentioned above. The method of derivation here under discussion is shown in outline form below. It may lead to new results of two kinds:

1. It may show that two well-known equations are each valid under certain conditions, but (a) that these cannot be re-

[31] C. Eckart, "Thermodynamics of irreversible processes, Parts I and II," Phys. Rev. 58, 267, 269 (1940).

alized simultaneously, or (b) are not realized in the ocean.

2. It may show that two phenomena—such as thermal convection currents and sound waves—interact in hitherto unsuspected ways (second-order effects, not necessarily small).

PROPOSED THEORETICAL STUDY OF THERMAL FIELDS AND ACOUSTIC PHENOMENA IN THE SEA

1. Thermodynamic Considerations.
   - 1.1 Pressure and Entropy Gradients as Functions of Temperature and Density Gradients.
   - 1.2 Numerical Data on Water (Pure and Sea).
2. The Basic Equations.
   - 2.1 Introduction of the Results of 1.1 into the Equations of Reference 31.
3. Observational and Dimensional Considerations.
   - 3.1 Choice of Units.
   - 3.2 Choice of Perturbation Parameter.
4. The Zero-Order Equations.
   - 4.1 Linear Gradients.
   - 4.2 Other Static Solutions.
   - 4.3 Periodic Solutions.
   - 4.4 Boundary Conditions.
5. The First-Order Equations.
   - 5.1 Small Perturbations of Linear Gradients.
     - 5.11 Steady States.
     - 5.12 Periodic Solutions.
       - 5.121 Sound Waves.
       - 5.122 Thermal Waves.
       - 5.123 Transverse Viscous Waves (Vortices).
   - 5.2 Small Perturbations of Other Gradients.
   - 5.3 The Quadratic Integrals and Their Relation to the Energy Principal.
6. The Second-Order Equations.
   - 6.1 Simplification by Means of the Results of 5.3.
   - 6.2 The Generation of Vorticity, etc.
   - 6.3 The Generation of Harmonics of the First-Order Perturbation, and the Mixing Problem.
   - 6.4 The Energy Budget.
7. Statistical Treatment of Aperiodic Solutions.
   - 7.1 Statistical Parameters of the First-Order Solutions.
   - 7.2 Statistically Steady States.
   - 7.3 The Approach to Thermal Equilibrium.
     - 7.31 Time Variation of the Standard Deviation of the Temperature.
     - 7.32 The Decay of Convective Turbulence.
     - 7.33 Second-Order Interaction of Thermal Waves (Statistical Aspects of 6.2 and 6.3).
   - 7.4 Second-Order Interactions of a Sound Wave and an Aperiodic Thermal Field.

This method has recently been used to investigate the generation of fluid streams by sound waves.[32] The results obtained are of the second kind mentioned above, and were not generally known, although they had been derived, in essentially the same manner, by Rayleigh (reference 14, Vol. II, p. 333).

The statistical aspects (item 7 in the outline) have not yet been investigated in any detail, but a preliminary survey does not reveal any insurmountable difficulties. In particular, the problems listed under item 7.4 should be amenable to mathematical techniques that have been developed in the quantum theory of the absorption and scattering of electromagnetic and material radiations.

The Marine Physical Laboratory of the University of California plans to undertake a program such as is here outlined. It is estimated that, with presently available staff, enough results can be obtained in twelve months so that a reliable judgment of the program can be made. It also seems very probable that, even if the fluctuation problem should not yield to this attack, useful results concerning the thermal fields in the ocean will be obtained.

The Theory of Semideterminate Functions

It has been indicated above that the empirical functions of geophysics are apt to be obtained in the form of wiggly graphs, to which it is impossible to fit simple analytic functions. This general fact is well illustrated by the fluctuation phenomena here discussed.

The mathematical theory of wiggly graphs may be called the theory of semideterminate functions, although the terms "random functions," "noise functions," "Stochastic," etc., are

[32] C. Eckart, "Fluid streams and vortices caused by sound waves," Phys. Rev. (to be published shortly).

also in use. It is a relatively young theory—little work was done prior to 1900 in this field. Recently a marked increase in activity has been apparent.[33-36]

Among other things, semideterminate functions are everywhere non-analytic. This means that, for every value of the independent variable or variables, the function or one of its derivatives has a discontinuity or singularity. This is largely responsible for the abstract and advanced level of the mathematics in reference 34. By considering a subclass of semideterminate functions that are continuous and have continuous first and second derivatives (the singularities all occur in the higher derivatives and are of a restricted kind), the theory is much simplified without materially restricting its applicability to geophysical and engineering problems. References 35 and 36 indicate that many important theorems about such functions can be proved without more advanced mathematics than the calculus.

The systematic development of this mathematical field will be of importance to geophysics as well as to other branches of science. It will be necessary to develop certain portions in connection with the experimental work planned by the Marine Physical Laboratory. This will be done at a priority level not to conflict with the theoretical work outlined in the previous section.

Solutions of the Wave Equation

Another mathematical field whose development would assist the study of underwater sound phenomena is the development of methods for the solution of special cases of the wave equation.

These special cases are of several kinds. One kind concerns boundary surfaces whose equation involves semideterminate functions; in another the phase velocity is a semideterminate function of the space and time coordinates. To a lesser extent, the geometric optics of such problems is of interest, and has been studied to an extent.[27, 28]

The general problem of refraction and shadow zones is important in underwater sound work. While its solution would be useful in connection with fluctuation, and also has wider uses, it will only be mentioned here.

Proposed Experimental Research

The general attitude of those who have been concerned with the experimental phases of work on fluctuation appears to be about as follows:

(a) The accumulation of further data with apparatus, such as has been used in the past, under uncontrollable conditions, is undesirable.

(b) There is no confidence that the summation of a number of special controlled situations will give a generalized answer, unless theoretical research makes radical advances.

(c) Any further work must be carefully planned with reference to statistical analysis.

Despite this disposition to doubt the value of further experimental work at this time, some experimental work appears to the writer to have some chance of either adding to our knowledge, or of preparing for the future.

Automatic Methods of Data Analysis

The semideterminate functions involved in geophysics are characterized by various numerical parameters, such as the standard deviation, etc. Much of the information embodied

[33] S. O. Rice, "Mathematical analysis of random noise," Bell Sys. Tech. J. 23, 282-332 (1944); 24, 46-156 (1945).

[34] N. Wiener, *The Extrapolation, Interpolation and Smoothing of Stationary Time Series with Engineering Applications* (MIT, DIC Contract 6037, February 1, 1942).

[35] Sonar Data Division, *An Introduction to the Theory of Time-Series* (UCDWR M408, August 12, 1946).

[36] Sonar Data Division, *The Sea Surface and Its Effect on the Reflection of Sound and Light* (UCDWR M407, March 20, 1946).

in a long wiggly graph, drawn by a recording galvanometer, and possibly occupying a length of many feet of paper, can be condensed into a graph of the autocorrelation coefficient that occupies only an 8″ x 11″ sheet. Other similar graphs are the distribution functions, etc. The objective of theoretical research must be to determine equations connecting these parameters of the semideterminate functions, or the equation of the autocorrelation coefficient graph, etc.

This remark emphasizes another difference between the laboratory and observational sciences: the step of determining the parameters and autocorrelation graphs is not present in laboratory work. In geophysical work it is essential, and involves much tedious arithmetic and reading of graphs. It can be the bottleneck that prevents progress, or the bogey that causes hesitation before an experiment whose success is not assured.

The development of automatic methods of performing this preliminary analysis would materially aid progress in all other work. The Marine Physical Laboratory is engaged in the development of a device (or better system of devices) for this purpose. Briefly the plan is

1. To record the empirical semideterminate functions on film in the form of a sound track (possibly modified for these special purposes).

2. To eliminate the labor of reading a long graph and converting it into numbers by using a photoelectric cell to scan the film and convert the record into a variable electric voltage.

3. The arithmetical operations are to be performed electronically by means of circuits whose outputs are proportional to the desired parameters when the variable voltage is applied to them.

Some progress has been made on this development, and it is expected that a preliminary version of the system will be in operation within the year. It is very possible that, for some purposes, the component devices can be embodied directly in the field equipment and thus eliminate the need for the complete system. However, the development program has adopted the complete system as its objective, leaving possible simplifications for the future.

Fluctuation Mechanisms in the Body of the Sea

In discussing theoretical research and the basic character of geophysical problems, the need to consider the effect of many simultaneously operative factors has been emphasized. Naturally, this does not relieve the experimenter of the responsibility for devising methods of work that reduce the number of such factors to a minimum in every case, and of studying such segregated groups whenever possible.

The effects of all mechanisms involving the surface or bottom of the sea can be eliminated by suspending the apparatus well below the surface but not too near the bottom. In order to eliminate mechanisms that involve the relative motion of source and receiver, both may be mounted on platforms supported rigidly from the bottom. Under these conditions only the mechanisms inherent in the volume of the sea can influence the measurements. These mechanisms can be further subdivided into two general groups: the multiplicity of ray paths, and the corrugation of the wave front, although there is no sharp dividing line. Multiple paths can also be described as an extreme distortion of the wave front, resulting in a folded, multi-sheeted surface. In the former case, no interference can take place and the phenomena should be relatively independent of frequency. In the latter case, interference and diffraction can occur and the phenomena should be strongly dependent on frequency.

One experimental approach is thus the transmission of frequency modulated pulses having a high repetition rate. Presentation of the received signals on the CRO is arranged so that the sound amplitude is the ordinate and frequency the abscissa. The "spectrum" of the fluctuation will be simpler if the interfering

paths are many. If the paths are few, the "spectrum" peaks will be approximately the same height; the number of peaks will be proportional to the path differences; interference fluctuation will shift the peak position; corrugation fluctuation will change the average of the spectrum intensity. The variation of intensity of the lines may be analyzed to find the distribution in space and time of the corrugations. Such experiments are now being undertaken by the Marine Physical Laboratory using high frequencies.

Both groups of mechanisms depend on the space and time variations in the velocity of sound, and these, in turn, are largely dependent on the variations in temperature.

The local fluctuation of the sound velocity can be directly measured with an acoustic interferometer, which consists of two rigidly mounted transducers. One transducer acts as a source, the other as a receiver; interference occurs between the voltage developed in the receiver and the voltage applied to the source. If the transducer separation is s and the frequency change is $\triangle$ f, the least detectable fractional change in velocity is approximately $c/s \triangle f$. A transducer separation of 1 foot with the frequency of 5 megacycles will detect a change in sound velocity of 0.001 percent; this velocity change corresponds to temperature change in the sea of approximately 0.01 degree Fahrenheit, which is probably ample sensitivity.

For fluctuation investigations the interferometer possesses the advantage of measuring sound velocity changes, not only due to thermal variations but also due to any other cause, such as salinity variations or ocean current variations. It should be noted that the acoustic interferometer described above measures v/c, where v is the velocity of the medium. In this, it differs from Michelson's optical interferometer, which measures only v^2/c^2.

However, it is also desirable to segregate these causes and to make measurements of them simultaneously with those of sound velocity. This requires the use of thermometers with high sensitivity and a rapid response to changes. Their construction is not easy. Thermocouples require that the measuring element be electrically insulated from the sea. In order that the response be rapid without loss of sensitivity, the heat conductivity must be high and the electrical conductivity low; hence an insulator must be chosen whose Wiedemann-Franz ratio is unusually low. The insulating layer must also be exceedingly thin, yet reasonably strong. A thin crystalline quartz plate, cut perpendicular to the optical axis, may provide a solution, since the properties of quartz along this axis are unusual.

Insulated resistance thermometers can also be constructed. Their design is complicated by a further phenomenon, if alternating current is used for the resistance measurement. This is the tendency of the insulator—sea water combination to form an electrolytic condenser of high capacity. Consequently, uninsulated resistance thermometers have been used. These are subject to other limitations, and may be subject to systematic errors.

Holter[18] makes a number of suggestions concerning the study of thermal gradients, that should be considered in planning such work.

Fluctuation Resulting from Reflection

For the purposes of this discussion, we may adopt the ray theory, and think of this type of fluctuation as being due chiefly to fluctuation of the amplitude of the reflected sound owing to interference between the multiplicity of reflected rays and to variations in the orientation and curvature of the reflecting surfaces. If a direct sound path exists between source and receiver an additional fluctuation effect occurs; the resultant sound fluctuates because the reflected component fluctuates in phase as well as in amplitude. The fluctuation in phase and amplitude of the direct sound, which was discussed in the section entitled "Dependence

of Fluctuation on Refraction Conditions," has been shown by observation to be considerably smaller in magnitude at ranges out to 1000 yards and may be neglected in the following discussion.

Considerable data on this type of fluctuation has already been accumulated. However, practically all of the data include the same defect—namely, the source and receiver were mounted on ships. Vertical motion of the transducers due to pitch and roll introduces additional fluctuation. More data is needed in which such fluctuation has been excluded. As has been mentioned previously, Liebermann and Yaspan[12] obtained such data by mounting transducers on towers which rested on the sea bottom. Submarines also offer good possibilities as transducer carriers in order to eliminate vertical motion.

In addition to the above defect, practically all present data include interference with the direct ray; observation of the amplitude distribution of the reflected ray alone would be more useful in correlating fluctuation with the state of the sea surface. Separation of the direct from the reflected sound may be effected by using deep transducers and short pulses in order to resolve the travel time of the reflected and direct sound. Liebermann and Yaspan[12] resolved the direct and reflected sound with the use of frequency modulated pulses. At higher frequencies it may be possible to make the beam width sufficiently narrow to obtain the separation by the use of directional hydrophones.

Eckart[28] has developed a theory of the reflection from the sea surface when the wavelength of the radiation is small compared to surface irregularities. In this case sound and light will behave analogously and experiments performed with the latter may be applied to sound. Such observations may include photographic data on the reflection of point light sources at various angles and with varying sea states, and may result in determining the parameters of the sea surface.

In order to compare any quantitative fluctuation theory with observation, data must be obtained on these parameters, and the experimental problem is a difficult one. Furthermore, as in all geophysical observations the data becomes vastly more useful if a simultaneous correlation can be established; fluctuation should be measured simultaneously with observation of the sea surface. One possible method of profile measurement at low sea states is the use of a large number of damped, vertically floating poles all tied together like a picket fence. Each pole is painted with a clearly defined depth scale. Photography of the group with a Cine' camera will yield an instantaneous as well as a time-dependent measurement of the profile. The reduction of this photographic data to the numerical parameters of the sea surface will be laborious, and, if possible, the optical method mentioned above should be elaborated into a more "direct-reading" method.

Utilization of Existing Data

The original oscillograms, obtained by UCDWR during the study of transmission at 24-kc and lower frequencies, are being maintained at NEL. There are several hundred miles of such records, showing the amplitudes of successive transmissions for long periods under various oceanographic conditions. The value of this data should not be underestimated, although it is difficult to utilize at present.

There are two reasons for this. As has already been remarked, it was taken in an attempt to obtain over-all correlations, without the guidance of an adequate theory. The usefulness of this data should increase as theory develops, and as it is supplemented by carefully designed experiments.

The other difficulty in utilizing it is the amount of labor required to read the oscillo-

grams and compute the parameters arithmetically. There is a possibility that photoelectric scanning devices can be constructed and the computation performed automatically. This will not be simple, as such an operation was not contemplated in designing the original recorders. For this reason, such a project should not be undertaken until experience has been gained in using such equipment under less handicapping conditions.

Psychophysical Experiments

It appears probable that the use of underwater sound for the transmission of intelligence will increase. The effect of distortion and fluctuation on the perception of signals is a matter that lies beyond the scope of this report. It is considered to be an important and probably fruitful field of study to which some effort should be devoted.

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CHAPTER

6

1. INTRODUCTION

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POSSIBLE TECHNIQUES OF IMPROVING AUDITORY DISCRIMINATION

Recognition of Underwater Sounds

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1. INTRODUCTION

The conversion of sonar information into action generally involves humans. The purpose of this paper is to outline the places where immediate need for applied and basic research in connection with sonar recognition exists. In the first part which follows, specific problems related to echo-ranging and listening systems are outlined. These applied topics are probably best performed in a government research laboratory, where continuity of effort and emphasis in obtaining answers of immediate value to the Navy are readily possible.

In the second part of this paper basic problems of hearing in need of research are outlined. These problems involve three principal fields: psychophysics, psychophysiology, and physicophysiology. The principal problems falling in these three fields include experiments using: noise stimuli; noise plus discrete tone stimuli; modulated signals and short pulses of sound. These particular problems are of types suitable for inclusion in a university program, where solutions of specific Navy problems are not as readily handled. Other subjects discussed include auditory fatigue, possible techniques of improving auditory discrimination, and the selection and training of sonar operators.

The critical reader will observe that little mention is made of basic research problems in the field of vision. We are well aware that there are problems in vision associated with sonar which are badly in need of investigation. Unfortunately, the illness of one of our colleagues prevented preparation of material on this subject. We hope that by analogy the reader will see places where basic research in this field is necessary.

2. APPLIED RESEARCH

General Aspects of Sonar

Sonar, an applied science of underwater sound, is constantly growing in importance because it provides man's most effective underwater "eyes." Its primary objective is to gather as much information from as large an undersea area as possible. Toward this end sonar systems must be designed (1) to gather a maximum of sonic information in a minimum time and (2) to portray it as effectively as possible

to the sonar operator, and/or the officer in charge. This leads to considerations of a dual nature in the sonar development problem: (1) the relation to engineering principles of the physical laws governing the maximal accumulation of underwater data and (2) the relation to design problems of the psychophysical principles involved in optimal portrayal. This implies concern with physical considerations supplemented by a study of the perceptual capabilities of human beings. The problem is to engineer a system to gather data in a manner best suited to human capacities. The most realistic approach is, of course, from both directions simultaneously, from engineering and from psychophysics. It is, therefore, most important that both the experimental psychologists and the developmental engineers be continuously apprised of the existing problems and of the efforts directed toward their solution.

In its present state, sonar systems are divided into two main classes, echo ranging (active sonar) and listening (passive sonar). The former tells the operator whether there is a sound reflecting object in the vicinity, gives its bearing, range, depth, and tells whether it is approaching or receding, and at what rate. The latter tells the operator whether there is a sound-emitting object in the vicinity, its bearing, and other pertinent information, including perhaps its identity, depending very much upon the nature of the sound and upon the experience and training of the operator. With each type of system much study of an applied and fundamental nature remains to be done to assure optimal results. Such studies now in progress follow three major lines. These are:

(a) Studies on the propagation of underwater sound.
(b) Studies on characteristics of sound transducers and interfering noises.
(c) Studies on portrayal and perception of information.

Research under item 3 consists of psychophysical studies involving the portrayal of material which is originally acoustic and its detection by either aural or visual means, or by some combination of the two. Thus, the sound received by the hydrophone at either sonic or ultrasonic frequencies can be presented to the ear by transducers, to the eye by cathode-ray oscilloscope, or by some recording device such as sensitized paper charts, etc. The following sections will attempt to indicate the more specific nature of the problems which are encountered in carrying out a general research program on sonar portrayal and detection in an applied research laboratory. This embraces echo ranging and listening.

Detection of Sonar Signals

General

The most general and fundamental problem is that of determining whether a signal (wanted sound) is in fact being displayed effectively from the point of view of the operator. This is generally not a problem involving the absolute threshold of hearing or of seeing, because sonar systems are normally engineered and operated with sufficient amplification to make the background noise audible or visible. Thus the first and most basic problem is differentiation from the masking background of the particular sound or light pattern associated with the signal. After that, differentiation between simultaneous or successive signals may be required so that the psychophysical problems involved are masked thresholds and difference limens. For underwater sounds, as presented to the sonar operator by one system or another, most of the psychological dimensions in audition and vision are important, and novel combinations, even within one sense modality, are frequently encountered. Sonar is a field of study in which the masked threshold is of primary importance. In communication, speech at its masked threshold of detection is of no practical use; it must reach some

specific level of intelligibility to be useful.[1] Sonar signals, too, may gain in usefulness as they rise above their masked thresholds, but the bare detection of a sonar signal provides one of the most important items of information sought—the knowledge of the presence of a target. This makes the masked threshold a very significant point. It is normally expressed in terms of the number of decibels the signal must exceed the background noise for 50 percent or some other prescribed probability of recognition. This quantity has been named the recognition differential, and has been studied for numerous systems and types of sounds.[2] This signal-to-noise ratio, expressed in decibels, provides a convenient measure of the effectiveness of various systems of portrayal. Its value depends primarily upon the nature of the signal and of the background noise, as well as upon the method of portrayal. A first step, therefore, in any study of sonar recognition is a thorough analysis of the sound to be detected and of the interfering background sound. To be most useful both the frequency and the time structures require analysis. Acoustic spectra should be obtained by an analyzer with a resolution of 50 c.p.s. or less to assess the auditory masking in terms of intensity level in the "critical bands."[•] The time resolution required depends on the portrayal to be made. A time constant of 50-200 milliseconds appears adequate for aural detection but gives too much smoothing for some visual purposes. The sound spectograph[3, 4] provides an excellent means of obtaining both time and frequency analyses simultaneously, particularly in view of recent advances in its quantitative portrayal of intensity.

[1] N. B. Gross and J. C. R. Licklider, *The Effects of Tilting and Clipping upon the Intelligibility of Speech* (Psycho-Acoustic Laboratory, Harvard University, Report PNR-11, April 15, 1946).

[2] Report No. M431, Univ. of Calif. Div. of War Research, September 30, 1946.

[•] The critical band at any frequency is essentially the band width of random (white) noise which is effective in masking a pure tone centered in the critical band. Its value is a function of frequency, varying from approximately 35 c.p.s. to 200 c.p.s. for two-ear listening. See H. Fletcher, "Auditory patterns," Rev. Mod. Phys. **12**, 41 (1940); also N. R. French and J. C. Steinberg, "Factors governing the intelligibility of speech sounds," J. Acous. Soc. Am. **19**, 90 (1947).

Specific Problems

Echo-ranging systems.—The principal problem in echo-ranging is one of detecting a short wave-train target (echo) from a background of sea reverberation, or from a background of noise which possesses a broad continuous spectrum. The major parameters are pulse (ping) duration, which generally varies from 1 to 200 milliseconds, and the frequency difference between echo and reverberation, which may vary from zero to several hundred cycles per second (Doppler). Both echo and reverberation vary in quality with pulse duration, but, except for the shortest pulses emitted, are essentially tonal. Research techniques using recorded sea sounds for investigating this field were developed by the Bell Telephone Laboratories and by the University of California, Division of War Research. Those developed at the latter consist of two synchronized sound-on film reproducers, one for background noise, and the other for signal. For example, in the case of detection of echoes masked by sea reverberation the two reproducers may be synchronized to keep the time of echo injection constant, or they may be adjusted to vary the time of injection (range of the simulated contact). The dependence of the recognition differential on ping duration for CW echo-ranging and for echoes with essentially rectangular envelopes and no Doppler has been reasonably well established for aural portrayal for both types of backgrounds.[2]

[3] J. C. Steinberg and N. R. French, "Portrayal of visible speech," J. Acous. Soc. Am. **18**, 4 (1946).

[4] R. K. Potter, G. A. Kopp, and H. C. Green, *Visible Speech* (D. Van Nostrand Company, Inc., New York, 1947).

Some work with the same sounds has been done on "A-Scan" cathode-ray oscilloscope presentation with reverberation masking. Study has also been made of the variation of the recognition differential with Doppler (frequency difference between echo and reverberation) where ping duration was the parameter.[2]

The character of background noise and echo varies with the type of echo-ranging equipment employed. Detection studies should therefore be made for all other types of sonar devices now extant. In addition to specific evaluation of these instruments thus achieved, such research will broaden the whole background against which new sonar developments may emerge. Both aural and visual presentation methods should be included in these studies.

In this connection, certain auditory problems requiring special attention may be mentioned. The first of these is the detection of short echoes, involving the various signal and background spectra from different sonars. Another is the effect of Doppler on the perception of such echoes. The dependence of recognition differentials on the shape of the echo envelope needs to be thoroughly explored.

In addition to the over-all comparison of systems involving aural portrayal, there is need for additional study of rectified *vs.* unrectified presentation and of linear *vs.* logarithmic amplitude scales for "A-scan" oscilloscopic methods. Other types of visual portrayal need investigation, such as the intensity-modulated cathode-ray oscilloscope as used in Plan Position Indication, with diverse types of tubes, sweeps, and screens. Echo portrayal by phase-sensitive methods is a promising field of study. This method would portray a coherent wave train (echo) in the form of a familiar pattern such as a line or circle, recognizably different from the background of reverberation or random noise. Included in the visual detection studies should be the determination of recognition differentials for portrayal on relatively permanent sensitized recording tapes which provide more "memory" advantages that the persistent oscilloscope screens. Cumulative advantage from this memory factor may arise by having a whole sequence of consecutive echo-reverberation traces visible simultaneously. This is being accorded attention in studies at the Navy Electronics Laboratory.

These visual methods should also be studied in combination with aural portrayal to determine any resulting enhancement of detection or possible deterioration due, perhaps, to division of attention between multiple systems.

Just noticeable differences for various characteristics of sonar stimuli need to be studied thoroughly. Such j.n.d.'s should involve masking backgrounds corresponding to those in sonar operation. Since the character of signal and background vary with the type of sonar equipment, the j.n.d.'s whose systematic study demands priority will depend upon which equipment requires development or evaluation most urgently.

Other relevant factors which might well be studied further concern the effects of the following features of signal/noise enhancement systems:

(a) very narrow filters.
(b) integrating, or envelope smoothing circuits.
(c) envelope-selective volume expansion circuits.
(d) noise cancellation circuits.

Most of these techniques for improving echo recognition have been nominally tested in the field but have not been carefully studied in controlled psychophysical tests in the laboratory.

Listening systems.—Although these systems comprise the oldest type of detecting devices, they have probably been less well explored than echo ranging. One reason for lag here is the complexity of the problem due to the wide range in spectral constitution of the various

sounds encountered—involving subsonic to ultrasonic frequencies and simple tonal to extremely complex noise spectra.

The determination of the optimal frequency band width for aural detection of propeller noise masked by a noise of similar spectrum is very important. This will determine the frequency above which it is profitable to use heterodyne listening and will fix the frequency to which other frequencies should be heterodyned. Such a study could be carried out with recordings of the actual sounds, or perhaps a more basic approach would utilize random noise. The propeller noise is ordinarily detected first as an intensity change in the noise background; thus, a study of the intensity difference limen for bands of random noise as a function of band width and center frequency would hold considerable promise. The influence of the temporal pattern of the intensity changes should also be studied.

The determination of the optimal rate of training a directional hydrophone across the target bearing is an allied problem requiring investigation. The purpose would be to determine that sweep procedure which will make best use of the change of loudness and quality of the signal, in order to insure the aural detection of weak signals, and to secure the greatest accuracy in determining target bearing.

Another allied study would investigate the dependence of the recognition of ships' screw sounds on the character of the modulation pattern, i.e., rhythm, rate of modulation, degree of modulation, etc.

Study should be made of the cues available in the acoustic output of ships which might be utilized through aural or other types of portrayal (1) to identify type or class of target and (2) to determine the target aspect. Some work has been done toward both of the above ends with aural portrayal.[5] A more complete study should be carried out and evaluation in terms of other means of portrayal, such as the sound spectrograph, attempted.

In addition to auditory research, determination of the recognition differentials for various types of visual portrayal of target sounds should be made in order to determine the most effective method of presentation for detecting weak signals. Such a study should include both continuous spectra and discrete frequency components. Some suggested methods of portrayal to be compared with aural methods are:

(a) The sound spectrograph or its cathode-ray oscilloscope adaption as used for visible speech. Parameters to be studied here should include scanning band width and rate, and frequency coverage, all of which are related.

(b) Listening-scanning systems using sensitized recording paper which is marked by a stylus synchronized with a continuously rotating hydrophone bearing. This device has the "memory" advantage of the recording paper mentioned earlier in connection with echo ranging.

(c) Phase-sensitive portrayal on a cathode-ray oscilloscope using pick up from two halves of a split hydrophone. This method was also referred to earlier.

Other Studies

The limits for noise tolerable in the sonar hut should be established, especially in relation to the detection of weak signals. These preferably should be set up in terms of noise spectra rather than over-all levels, and should be determined with regard to the particular gear installed, its location, and special uses and type of ship involved. Thus, the types of sonar gear aboard submarines may require different noise limits from those required by the types installed on destroyers.

As visual portrayal becomes more prevalent, environmental conditions necessary for optimal visual detection should be stated. In view of the visual studies already underway in the

[5] Report No. M400, Univ. of Calif. Div. of War Research, April 15, 1946.

field of radar, a program designed to assimilate this information into sonar seems warranted.

It seems probable that sonar on certain types of ships may find a central information system necessary, similar to the Combat Information Center, together with its attendant problems. It is also quite clear that many of the recognition problems already referred to will ultimately encompass study of the effects of learning, motivation and fatigue on the detection of weak signals.

Studies in Sonar Recognition Related to Selection and Training

In the course of recognition studies with all kinds of sonar equipment, knowledge of the human capacities required for best detection of a signal with a particular type of portrayal should emerge. A job analysis of the psychophysical aspects of sonar may, therefore, result. Further understanding of operational requirements comes from close association of the researchers with units of the Fleet and with the Fleet Sonar Schools at San Diego and Key West. Such associations have resulted in valuable selection studies from the Submarine Base at New London[6, 7] and the Navy Electronics Laboratory (including its predecessor, the University of California Division of War Research).** The study of tactical parameters is especially aided by contact with the Fleet Sonar Schools. Growing out of the detection studies, therefore, is the need for tests to measure the various sensory-perceptual capacities of significance in selecting men for sonar operator training. Such tests may be used as screening devices, when sufficiently well validated, and for training purposes. They will be, of course, only one facet of a selection battery, of many components.

Many of the recordings of underwater sounds collected for use in the psychophysical studies may also be used in developing training materials for course instruction in the sonar schools.

3. BASIC RESEARCH

Methods of Investigation

In basic research on the problems of sonar recognition, three classes of methods may be used, namely, psychophysical, physicophysiological, and psychophysiological.

Psychophysical Methods

Psychophysical methods are those in which the independent variables are various attributes of the physical stimulus, e.g., frequency, intensity, and complexity. The dependent variables are discriminatory responses of experimental subjects. Where human subjects are used these responses will, as a rule, be verbal reports; where lower animals are used, discriminations will be indicated by overt motor reactions. Standard procedures used in psychophysical studies are in common use in the psychological laboratory. See, for example, Guilford,[8] Stevens and Davis,[9] and Thurstone.[10]

Physicophysiological Methods

In studying the physiological changes evoked by changes in the physical stimulus, the independent variables are again attributes of the physical stimulus, such as intensity, fre-

[6] J. D. Harris, *Functions of Pitch in Submarine Sonar Operation* (New London Submarine Base, January 30, 1945).

[7] J. D. Harris, *Functions of Loudness Discrimination in Submarine Sonar Operation* (New London Submarine Base, April 5, 1945).

** See Completion Report Univ. of Calif. Div. of War Research (at the Navy Electronics Laboratory, San Diego).

[8] J. P. Guilford, *Psychometric Methods* (McGraw-Hill Book Company, Inc., New York, 1936).

[9] S. S. Stevens and H. Davis, *Hearing* (John Wiley and Sons, Inc., New York, 1938).

[10] L. L. Thurstone, *Psychophysical Methods* (Ed. T. G. Andrews, John Wiley and Sons, Inc., New York (in press), Chapter V: "Methods of psychology."

quency, and complexity, but the dependent variables, in this case, are directly recorded physiological changes in the auditory system. The physiological changes which have been most commonly used in the past are the microphonic response of the cochlea and the action potentials of the auditory nerve or of the higher neural pathways.[9, 11-13] Recently Békésy[14] has developed a technique which makes possible visualization of movement of cochlear structures. This method appears to have much promise. Experimental subjects in physicophysiological investigations will usually be lower animals.

Psychophysiological Methods

Finally, it is necessary to relate physiological changes and psychological phenomena. The independent variables will be experimentally produced alterations of the physiological mechanism of hearing, i.e., of the middle ear, inner ear, or neural structures; and the dependent variables will be discriminatory responses of the experimental subjects.

As in physicophysiological studies, animals will necessarily be used as experimental subjects in most psychophysiological experiments. Methods have been developed which make possible accurate determination of the ability of animals to discriminate changes in auditory stimuli.[15-18] Some information may also be derived from clinical studies of man in which variation of the auditory structures is produced by disease or other natural causes rather than by the experimenter.[19, 20]

Studies Suggested by Field Research in Underwater Acoustics:

Experiments Using Noise Stimuli

Auditory theory has been founded, in large part, upon experiments in which pure-tone stimuli were used. Field investigations, such as those in underwater acoustics, indicate the inadequacy of present auditory theories in dealing with problems relating to sounds with complex spectra. An extension of basic research to include a detailed analysis of how the auditory system functions when activated by stimuli of complex frequency spectra is, therefore, suggested.

In the field laboratory, noise stimuli used in experiments are, more often than not, designed to simulate as exactly as possible the actual noises which occur in the field. For example, careful film or disk reproductions are made of the cavitation noise produced by a ship's propellers and of the ambient water noise. For basic studies, a constant and controllable noise source is required. Therefore, random (or "white") noise in which all frequencies are present and the spectrum of the sound is continuous is to be preferred.

Determination of Psychophysical Relationships

With white noise stimuli, the psychophysi-

11 E. G. Wever, "The Electrical responses of the ear," Psychol. Bull. 36, 143-187 (1939).

12 R. Galambos and H. Davis, "The response of single auditory-nerve fibers to acoustic stimulation," J. Neurophysiol. 6, 39-57 (1943).

13 F. Bremer and R. S. Dow, "The cerebral acoustic area of the cat. A combined oscillographic and cytoarchitectonic study," J. Neurophysiol. 2, 308-318 (1939).

14 G. V. Békésy.

15 E. Culler, G. Finch, E. Girden, and W. Brogden, "Measurement of acuity by the conditioned response technique," J. Gen. Psychol. 12, 223-227 (1935).

16 W. J. Brogden and E. A. Culler, "Device for the motor conditioning of small animals," Science 83, 269-270 (1936).

17 W. E. Kappauf, "The application of conditioning methods to the study of discrimination and the measurement of differential thresholds in animals," J. Psychol. 15, 129-135 (1943).

18 M. Rosenzweig, "Discrimination of auditory intensities in the cat," Am. J. Psychol. 59, 127-136 (1946).

19 S. J. Crowe, S. R. Guild, and L. M. Polvogt, "Observations on the pathology of high-tone deafness," Bull., Johns Hopkins Hosp. 54, 315-379 (1934).

20 S. R. Guild, "Tone localization in the cochlea II. Discussion from the point of view of studies on human temporal bones," Ann. Otol., Rhinol., Laryngol. 44, 738-753 (1935).

cal experiments ordinarily performed with pure tones can be paralleled, and changes in the psychological phenomena of loudness and pitch as a function of such variables as band width, intensity, and region of the frequency spectrum can be determined. Measures of the differential thresholds of loudness and pitch as a function of these same variables may also be obtained. A number of psychophysical studies using white noise stimuli have been carried out by the Psycho-Acoustic Laboratory, Harvard University. For example, recorded tests which measure ability to discriminate the pitch and loudness of noises have been developed by Karlin.[21] Preliminary results on the use of the loudness discrimination tests in the selection of sonar operators have been reported by Harris.[7] Miller[22] has measured sensitivity to changes in intensity over a wide range of intensities; from these measurements he has found that

> "the just detectable increment in the intensity of the noise is of the same order of magnitude as the just detectable increment in the intensity of pure tones. For intensities more than 30 db above the threshold of hearing for noise the size in decibels of the increment which can be heard 50 percent of the time is approximately constant (0.41 db)."

He also found that, as for pure tones, just noticeable differences at different intensity levels are not equal in subjective magnitude, the j.n.d. at low intensity levels appearing smaller than at high levels. (See below for discussion of the relation of these results to the phenomenon of masking.)

[21] J. E. Karlin, *Auditory tests for the ability to discriminate the pitch and loudness of noises* (OSRD Report No. 5294, Psycho-Acoustic Laboratory, Harvard University, August 1, 1945).

[22] G. A. Miller, "Sensitivity to changes in intensity of white noise and its relation to masking and loudness," J. Acous. Soc. Am. 19, 609-619 (1947).

Measurement of Physiological Events

Physicophysiological experiments which may be performed with white noise stimuli include determination of changes in cochlear microphonics and nerve potentials as a function of the different variables of the physical stimulus.

Effect of Physiological Changes on the Hearing of Noise Stimuli

Psychophysiological experiments may be concerned with changes in hearing of noise stimuli as a result of alteration of the physiological mechanism. For example, absolute thresholds of hearing for pure tones and for different bands of white noise can be measured before and after lesions of the cochlea or auditory nervous system.

To date, there are no reports available of research projects that might be classified under "General Aspects of Sonar" and "Detection of Sonar Signals."

Masking Experiments

Since one of the most important tasks of the sonar operator is the detection of an auditory signal which is more or less masked by a background of sound, studies of masking are of major practical importance in underwater acoustics. Moreover, it is in this area, the study of masking phenomena, that the field research appears most suggestive to the experimenter in the University laboratory.

Beginning with the classical study of Wegel and Lane,[23] we have had numerous investigations of the masking of one pure tone by another. With the exception of the experiments on the masking of speech by noise, which were carried on for the most part in the Bell Telephone Laboratories, there were almost no studies prior to World War II of the masking

[23] R. L. Wegel and C. E. Lane, "The auditory masking of one pure tone by another and its probable relation to the dynamics of the inner ear," Phys. Rev. 23, 266-285 (1924).

effects of noise on pure tones or of noise background on noise signals. The work of the laboratories investigating the problem of underwater acoustics and of other laboratories studying the problems of communication in noise have emphasized this lack of knowledge.

Masking of Pure Tones by Noise

The Harvard Psycho-Acoustic Laboratory has recently published the results of a series of experiments on the masking of pure tones by white noise.[24] Tests were made at 8 noise levels ranging from 20 to 90 decibels. Results were used to determine two basic functions:

"(a) The critical band width of a masking noise, i.e., the ratio, in decibels, between the level of a pure tone and the level per cycle of the noise that is just able to mask the tone.

(b) The function relating the amount of masking to the effective level of the masking noise."***

Related studies have been reported by Harris[25] and Flynn, Truscott, and Newman.[26] Detectability as a function of signal duration has been investigated by the Sonar Data Division of the University of California Division of War Research, U. S. Navy Electronics Laboratory[2] in a series of experiments in which the signal was a short tonal pulse and the masking background was white noise. Further psychophysical investigations of this sort are indicated. For example, the concept of critical band width in masking noise has proved very useful in explaining masking phenomena with underwater sounds. Several factors associated with the concept should be studied further. Do significant individual differences exist in critical band width from person to person? If so, what is the correlation between critical band width and pitch discrimination? Is a person with better than average pitch discrimination also above average in detecting a weak tone in a thermal noise background? Furthermore, how does the hearing mechanism integrate signals received simultaneously from several critical bands? A study has recently been conducted on this problem at the Navy Electronics Laboratory, San Diego.

In the field of binaural perception, how does the masked threshold for "in-phase" two-ear (diotic) reception compare with that for binaural presentation where the signal varies in perceived azimuth? Does this type of "auditory motion" aid recognition of a signal through a masking background? Of interest also is the intensity difference between two ears necessary to reduce binaural acuity to its monaural value.

In addition to psychophysical investigations, physicophysiological, and psychophysiological experiments are required. As an example of the kind of information which may be obtained from such experiments, an experiment by Galambos and Davis[27] may be cited. These investigators found that the spontaneous discharge, which may be recorded from single nerve fibers of the auditory nerve, can be stopped by certain tones and noises. Furthermore, the discharge elicited by certain tones can be reduced or abolished by the simultaneous presentation of another tone or noise. This neural "inhibition" may play an important role in masking and its discovery must lead us to question the adequacy of the commonly accepted theory that masking occurs because the masking tone or noise activates the region of the cochlea and the nerve fibers

[24] J. E. Hawkins, *The Masking of Pure Tones and Speech by White Noise. Part I* (OSRD Report No. 5387, Psycho-Acoustic Laboratory, Harvard University, October 1, 1945).

*** Quoted from author's summary.

[25] J. D. Harris, "Pitch discrimination in noise," Am. Psychol. 1, 276-277 (abstract) (1946).

[26] J. P. Flynn, I. P. Truscott, and E. B. Newman, "Intensity discrimination as a function of signal-to-noise ratio and intensity level," Am. Psychol. 1, 277 (abstract) (1946).

[27] R. Galambos and H. Davis, "Inhibition of activity in single nerve fibers by acoustic stimulation," J. Neurophysiol. 7, 287-303 (1944).

ordinarily activated by the masked tone. It appears that masking is a more complex phenomenon physiologically than has usually been assumed and that extensive experimentation using the most refined recording techniques must be done in order that we may understand the interaction which apparently occurs in the peripheral fibers of the cochlear nerve and, undoubtedly, in the higher auditory centers as well.

On the psychophysiological level further data as to the analytical function of the auditory system can be obtained by experiments in which the masking effects of bands of noise on pure tones is determined in animals experimentally deprived of part of the sensory or neural elements of hearing. For example, will a band of frequencies, whose individual components are not heard because of experimental damage to the cochlear hair cells or auditory nerve, mask the hearing of frequencies unaffected by the lesion? Studies which have been made with pure tone stimuli[28-30] may be paralleled with the added variable of a masking noise background, making these studies more realistic.

Masking of Noise Signals by Noise Background

Experiments similar to those which have been described or suggested under the heading of "masking of pure tones by noise" should also be done using noise signals instead of pure tones. The degree of masking as dependent upon such variables as band width and modulation may be investigated. Only a few studies of this nature have as yet been undertaken. Experiments on masking of a noise signal, simulating the underwater sounds produced by a ship's screws, have been reported by the University of California Division of War Research,[31] by Harris,[32] and by Snow and Neff.[33] Miller[16] has pointed out that the results obtained in his experiments on sensitivity to changes in white noise may be regarded as measures of the masking of noise by noise. He points out that the "functions which describe intensity discrimination also describe the masking of white noise of pure tones and of speech" and that the determination of differential sensitivity to intensity may be considered as a special case of the more general masking experiment; viz., masking of noise by a noise background.

Residual Masking

Another aspect of the masking problem is that of short-time auditory fatigue, the effect of which we call residual masking. A laboratory study would investigate the masked threshold immediately after a short loud stimulus. This factor is closely associated with the audibility of sonar echoes in a background of irregularly amplitude-modulated sea reverberation. Such reverberation has a generally decaying envelope on which many "blobs" (echo-like peaks in the reverberation) are superposed. Echo durations of 10 to 200 milliseconds are of interest, injected at times of zero to 200 milliseconds after the preceding tone. An over-all study of the temporal integrative properties of the hearing mechanism, from ear drum to cortex, would provide extremely valu-

[28] K. D. Kryter and H. W. Ades, "Studies on the function of the higher acoustic nervous centers in the cat," Am. J. Psychol. **56**, 501-536 (1943).

[29] W. D. Neff, "The effects of partial section of the auditory nerve," J. Compar. and Physiol. Psychol. **40**, 203-215 (1947).

[30] E. G. Wever and W. D. Neff, "A further study of the effects of partial section of the auditory nerve," J. Compar. and Physiol. Psychol. **40**, 217-226 (1947).

[31] *Masking Experiments* (Report No. U258, University of California Division of War Research at the U.S. Navy Radio and Sound Laboratory, San Diego, California, September 15, 1944).

[32] J. D. Harris, *Preliminary Report on Propeller Noise Discrimination* (Report of the Medical Research Department, U.S. Submarine Base, New London, Conn., December 26, 1944).

[33] W. B. Snow and W. D. Neff, *Effects of Airplane Noise on Listening with Headphones* (Report of Columbia University Division of War Research at the U.S. Navy Underwater Sound Laboratory, Fort Trumbull, New London, Conn., January 25, 1943).

able fundamental information (notes [34, 35]).

Modulation

Problems encountered in studying the detection of echoes against a background of reverberations[2] suggest the need for experiments to determine the effects of amplitude, frequency, and phase modulation of pure tones upon the physiological processes and psychological phenomena of hearing.

For example, a determination of the optimal rate and extent of modulation for aural perception of a rhythmic beat in random noise would provide information related to detection of propeller noise.

The problem of modulation in relation to hearing has been discussed by Stevens and Davis[9] and a number of experiments cited: Weinberg and Allen,[36] Wingfield,[37] Stowell and Deming,[38] Seashore,[39] Ramsdell,[40] Youtz and Stevens.[41] These must be considered as preliminary only in view of the many variables yet to be explored. Investigations should be extended to the measurement of effects of modulation of complex sounds as well as of pure tones.

Hearing of Short Pulses of Sound

Stevens and Davis (reference 9, pp. 100-106 and pp. 154-159), have reviewed experiments (prior to 1938) in which short impulses of sound were used in studying auditory function. In their review are included psychophysical studies on pitch as a function of duration,[42, 43] the effect of duration upon the difference limen DL for frequency discrimination,[44] the threshold of successiveness—i.e., the minimum time of separation of two sounds in order that they appear as two rather than as one,[45, 46] loudness as a function of duration,[47-49] loudness as a function of the form of the pressure wave of the sound impulse[49, 50] and loudness as a function of the frequency of repeated impulse.[49]

In a recent experiment Turnbull[51] has examined the effect of stimulus duration upon pitch discrimination for pure tone stimuli of 128, 1024, and 8192 cycles. He has found that decreasing the duration of a tone to be com-

[34] M. B. Gardner, "Short duration auditory fatigue as a method of classifying hearing impairment," J. Acous. Soc. Am. **19**, 178 (1947).

[35] W. R. Garner, "Effect of frequency spectrum on temporal integration of energy in the ear," J. Acous. Soc. Am. **19**, 808 (1947).

[36] M. Weinberg and F. Allen, "On the critical frequency of pulsation tones," Phil. Mag. **47**, 50-62 (1924).

[37] R. C. Wingfield, "An experimental study of the apparent persistence of auditory sensations," J. Gen. Psychol. **14**, 136-157 (1936).

[38] E. Z. Stowell and A. F. Deming, "Aural rectification," J. Acous. Soc. Am. **6**, 70-79 (1934).

[39] C. E. Seashore, *The Vibrato* (University of Iowa studies in the psychology of music, 1932, 1).

[40] D. A. Ramsdell, *The Psycho-Physics of Frequency Modulation* (unpublished thesis, Harvard University).

[41] R. E. P. Youtz and S. S. Stevens, "On the pitch of frequency modulated tones," Am. J. Psychol. **51**, 521-526 (1938).

[42] S. S. Stevens and A. G. Ekdahl, "The relation of pitch to the duration of a tone," J. Acous. Soc. Am. **10**, 255 (abstract) (1939).

[43] W. Burck, P. Kotowski, and H. Lichte, "Der Aufbau des Tonhuhenbewusstseins," Elek. Nachr.-Techn. **12**, 326-333 (1935).

[44] G. v. Békésy, "Zur Theorie des Horens. Uber die eben merkbare Amplitudenund Frequenzanderung-eines Tones. Die Theorie der Schwebungen," Physik. Zeits. **30**, 721-745 (1929).

[45] F. Strecker, "Die Bomerkbarkeit von Einschwingzeiten," Teleg. und Fernspr.-Techn. **24**, 1-5 (1935).

[46] W. Burck, P. Kotowski, and H. Lichto, "Die Hurbarkeit von Laufzeitdifferenzen," Elek. Nachr.-Techn. **12**, 355-367 (1935).

[47] G. v. Békésy, "Zur Theorie des Horens. Uber die Bestmmung des einem reinen Tonempfinden ents prechenden Erregungsgebiates der Basilar membran vermittels Ermudungserscheinungen," Physik. Zeits. **30**, 115-125 (1929).

[48] S. Lifshitz, "Apparent duration of sound perception and musical optimum reverberation," J. Acous. Soc. Am. **7**, 213-221 (1936).

[49] U. Steudel, "Uber Empfindung und Messung der Lautstarke," Hochfrequenztechnik und Electroakustik **41**, 116-128 (1933).

[50] W. Burck, P. Kotowski, and H. Lichte, "Die Lautstarke von Knacken, Gerauschen und Tonen," Elek. Nachr.-Techn. **12**, 278-286 (1935).

[51] W. W. Turnbull, "Pitch discrimination as a function of tonal duration," J. Exper. Psychol. **34**, 302-316 (1944).

pared with a standard tone of fixed duration has slight effect upon the relative difference limen ($\triangle$FF) until the length of the comparison tone has been reduced to 0.1 to 0.5 second depending upon the frequency. At this point the difference limens begin to increase markedly. In the region of 0.01 to 0.03 second, accuracy reaches a virtual zero.

Turnbull also found that for a given duration of the comparison tone, decrease in intensity reduced the accuracy of pitch discrimination and that this reduction was greater for tones of relatively short durations.

Garner and Miller[52] have investigated the differential sensitivity to intensity as a function of the duration of the comparison tone. For tones of 500 and 1000 cycles, the former at sensation levels of both 40 and 70 db and the latter at 40 db only, they found that the relative difference limen (DII) was approximately constant for durations above 300 milliseconds. Below 300 milliseconds the reduction in accuracy of discrimination was much less rapid for the 500-cycle tone at a sensation level of 70 db than at 40 db. However, additional data should be obtained before any broad generalization about the effect of intensity level is made.

To further our knowledge of auditory function, numerous psychophysical studies in which duration of stimulus is a variable need to be performed. The results of Turnbull and of Garner and Miller should be extended to include tests with a wider range of frequencies and intensities. Functions, paralleling those for tonal stimuli, should be determined for noise stimuli. It would also be of interest to compare the loudness-duration functions for different intensity levels, intensity being measured as r.m.s., peak, and average pressures.

No attempt has been made to measure systematically the effects of short impulses, tonal or non-tonal, upon physiological mechanisms of the inner ear of auditory nervous system. A few observations have been made incidentally in the course of experiments aimed at the solution of other problems (reference 9, pp. 327-332 and pp. 386-411). Some very suggestive results have more recently been reported by Galambos and Davis in their studies of the activity of single fibers of the auditory nerve.[12, 27] They have noted that "equilibration," the decrease in voltage output of the auditory nerve following onset of sound stimulation, occurs in the single fiber preparation and is essentially complete within a few tenths of a second.[12] They have also made observations on the "inhibitory" or "masking" effect of a noise which consisted of a series of sharp clicks.[27] Brief atonal and tonal impulses have also been used in investigating the response of the higher auditory centers, especially the auditory cortex.[13, 53-56] Further experiments with controlled variation of duration and wave form of impulses should contribute to our understanding of the function of the auditory nervous system. Such experiments should include not only the recording of electrical activity of the nervous pathways and centers but also the measurement by behavioral methods of discriminatory ability before and after ablation of parts of the system.

Auditory Fatigue

By auditory fatigue is meant temporary

[52] W. R. Garner and G. A. Miller, "Differential sensitivity to intensity as a function of the duration of the comparison tone," J. Exper. Psychol. 34, 450-463 (1944).

[53] E. M. Walzl and C. N. Woolsey, "Effects of cochlear lesions on click responses in the auditory cortex of the cat," Fed. Proc. Am. Soc. Exper. Biol. 1, 88 (1942).

[54] J. C. R. Licklider and K. D. Kryter, "Frequency-localization in the auditory cortex of the monkey," Fed. Proc. Am. Soc. Exper. Biol. 1, 51 (1942).

[55] H. W. Ades and R. Felder, "The acoustic area of the monkey (Macaca mulatta)," J. Neurophysiol. 5, 49-54 (1942).

[56] A. R. Tunturi, "Further afferent connections to the acoustic cortex of the dog," Am. J. Physiol. 144, 389-394 (1945).

impairment of hearing sensitivity resulting from stimulation of the ear by sound.**** Experiments which have reported fatigue effects have usually used intensities of sound some 100 db re 10^{-16} watt/sq. cm.[33, 57-65] The sonar operator, during his ordinary duties, is probably seldom subjected to sounds of this intensity, and auditory fatigue may not be a factor of great importance in determining his proficiency. However, in view of such experiments as those of Rawdon-Smith[64, 65] in which he found threshold shifts as high as 56 db, resulting from stimulation by pure tones at 100-110 db above threshold and changes in differential sensitivity for frequency following stimulation by pure tones 70-100 db above threshold, it appears within the realm of possibility that repeated exposure of the ear to fairly loud sounds such as encountered by the sonar operator in echo ranging may affect the sensitivity to minimal intensity or differential sensitivity to frequency and intensity. Further information on the "fatique" or "inhibitory" effects of pure tone and noises, including intensities in the range 60-110 db, needs to be acquired. Brief impulses, as well as steady sounds, should be used and the effect of repeated exposures, without opportunity for recovery from any losses which appear, should be examined.†

**** Rawdon-Smith (reference 65) has suggested that the term "experimental deafness" rather than fatigue be used to describe the temporary hearing losses which he found to occur in human subjects following brief exposures to tonal stimuli in the range 100-110 db. above threshold. He also suggests the term "auditory inhibition" to refer to the part of this deafness which appears to be due to a central nervous system phenomenon. Wever (reference 11) in a review of experiments on electrical responses of the cochlea and auditory nervous system suggests that "in view of the extreme intensities (of sound) required (to produce depression in the electrical responses), and the long period taken for recovery, it would seem more appropriate to regard the effect as one of injury rather than as fatigue in the usual sense" and that "it is probable that stimulation deafness is a later and irreversible stage of the same injury process."

57 Final report on temporary deafness following exposure to loud tones and noise. Prepared by the Committee on Medical Research of the Office of Scientific Research and Development. Boston, Mass., Dept. of Physiology, Harvard Medical School, 1943. Reported under contract OEM cmr-194 (H. Davis, C. T. Morgan, J. E. Hawkins, Jr., R. Galambos, and F. W. Smith).

58 O.S.R.D. Report No. 889, July 31, 1942.

59 H. B. Perlman, "Acoustic trauma in man. Clinical and experimental studies," Arch. Otolaryngol. **34**, 429-452 (1941).

60 H. G. Kobrak, J. R. Lindsay, and H. B. Perlman, "Experimental observations on the question of auditory fatigue," Laryngoscope **51**, 798-809 (1941).

61 L. Ruedi and W. Furrer, *Das Akustische Trauma* (S. Karger, Basel, 1947).

62 B. Larsen, "Investigations in the fatigue of hearing," Acta Otolaryng. **30**, 525 (1942).

63 R. C. Parker, "The nature of fatigue in the auditory system," Proc. Phys. Soc. (London) **50**, 108-118 (1938).

64 A. F. Rawdon-Smith, "Auditory fatigue," Brit. J. Psychol. **25**, 77-85 (1934).

65 A. F. Rawdon-Smith, "Experimental deafness. Further data upon the phenomenon of so-called auditory fatigue," Brit. J. Psychol. **26**, 233-244 (1938).

Possible Techniques of Improving Auditory Discrimination

The ability of the sonar operator to detect the signal representing a target can be improved in two ways: (1) by advances in the design of equipment and (2) by the use of techniques which lower the discriminatory thresholds. The first of these has been a matter of major consideration on the part of the physicist and engineer. The second has received little direct attention, although a number of studies, aimed as a rule toward the solution of other problems, have produced results which deserve further consideration.

In a recent experiment, for example, Shaw, Newman, and Hirsh[66] have found that

† See H. Davis *et al.* (reference 57). These investigators found no cumulative effects when ears of human subjects were repeatedly exposed to intense tones and noise 110-130 db re 10^{-16} watt/cm^2. However, subjects were not re-exposed to the intense stimuli until recovery (as measured by the audiogram) from the previous exposure was complete.

66 W. A. Shaw, E. B. Newman, and I. J. Hirsh, "The difference between monaural and binaural thresholds," J. Exper. Psychol. **37**, 229-242 (1947).

"the absolute threshold for pure tones is lower when both ears are stimulated than when either ear is stimulated alone. The normal summation at threshold is a function of the relative sensitivity of the two ears. For a group of listeners with substantially normal hearing in both ears, the binaural threshold is from one to two decibels lower than the best monaural threshold."

Similarly, it has been found that smaller differences in frequency and in intensity can be detected when the stimuli are presented binaurally rather than monaurally (reference 9, pp. 87 and 141-142). These results are in part substantiated by physiological experiments which indicate that the absolute threshold for intensity is raised by the destruction of one cochlea.[67]

Several investigators,[68-70] (see reference 71 for review of these experiments) have reported improvement in auditory discrimination resulting from coincident visual stimulation. This phenomenon of intersensory facilitation is not well substantiated and is open to various interpretations. The possibility remains, nevertheless, that some real gains may be made by combined visual and auditory presentation of near liminal signals.

It has been a common observation on the part of researchers in audition that the ability to detect minimal intensities, to discriminate changes in frequency and intensity, and to recognize particular patterns of sound increases with practice. Studies such as that of Wyatt[72] on improvability of pitch discrimination are important additions to knowledge derived from more casual observations. Many additional investigations must be conducted before we shall know with any degree of certainty the limits of improvement, individual differences in improvability, the degree of transfer of training from one particular type of discrimination to another, the most effective training procedures, and the factors which account for improvement.

Significant improvement in auditory discrimination may sometimes be brought about by new and unexpected discoveries. Potentially promising is the recent observation that interaural phase relations affect the detectability of a tone heard against a background of noise.

When a tone is presented to both ears against a background of noise, the tone is more easily heard if it is in phase at the two ears while the noise is out of phase (or vice versa) than when both the tone and the noise are either in phase or out of phase. For example, when a tone of 200 c.p.s. is led to the two ears along with white noise, the detectability of the tone is improved by as much as 13 db merely by reversing the interaural phase of the tone and leaving the noise alone: this phase is an important factor.

It is even possible to improve the detectability of a tone simply by reversing the connections to one earphone, thereby making the interaural phase of both the tone and the noise 180°.

These laboratory findings may or may not prove applicable to sonar listening. The important point is that through the prosecution of vigorous research in University Laboratories new and unsuspected facts and princi-

[67] W. J. Brogden, E. Girden, F. A. Mettler, and E. Culler, "Acoustic value of the several components of the auditory system in cats," Am. J. Physiol. **116**, 252-261 (1936).

[68] L. Freund and L. Hofmann, "Licht und Hozen," Med. Klinik **25**, 226-228 (1929).

[69] G. W. Hartmann, "The facilitating effect of strong general illumination upon the discrimination of pitch and intensity differences," J. Exper. Psychol. **17**, 813-822 (1934).

[70] I. L. Child and G. R. Wendt, "The temporal course of the influence of visual stimulation upon the auditory threshold," J. Exper. Psychol. **23**, 108-127 (1938).

[71] T. A. Ryan, "Interrelations of the sensory systems in perception," Psychol. Bull. **37**, 659-698 (1940).

[72] R. F. Wyatt, "Improvability of pitch discrimination," Psychol. Monog. **58**, No. 2, 1-58 (1945).

ples will continue to emerge in a steady stream. Some of these discoveries will have a revolutionary impact on the military art, suggesting, perhaps, many improvements.

Finally, a study of the optimal method of enhancing perception of sounds below 100 cycles per second would have many practical applications. How can the ear be aided at low frequencies where its sensitivity deteriorates? The following possibilities exist:

(a) frequency translation,

(b) amplitude modulation of audible carrier,

(c) visual methods, for example, the sound spectrograph as a "visible speech" device.